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Black Holes

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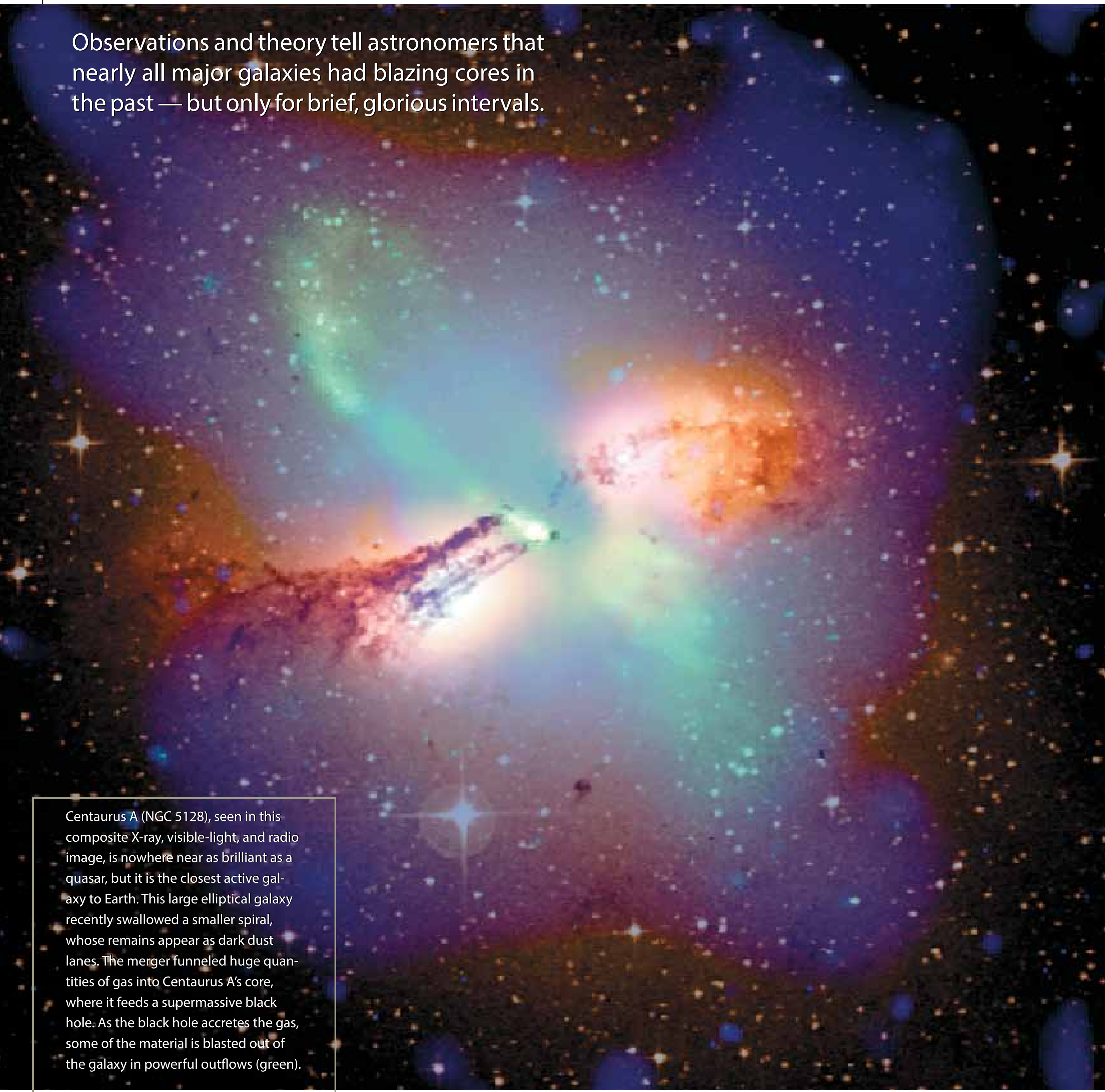
Black Holes

FRONT COVER AND ABOVE: MARK GARLICK

Black holes capture the imagination. These rents in the fabric of spacetime let nothing, not even light, escape. Yet when they feast, supermassive black holes nesting in galaxy centers become powerful beacons. As gas flows into their gaping maws, it heats up, glowing brightly enough to be seen from the early universe.

Four articles from past issues of *Sky & Telescope* reveal the mysteries of supermassive black holes, how they form, and the role they play in galaxy formation. One day, we might even be able to observe the beasts themselves. ✦

Observations and theory tell astronomers that nearly all major galaxies had blazing cores in the past — but only for brief, glorious intervals.



Centaurus A (NGC 5128), seen in this composite X-ray, visible-light, and radio image, is nowhere near as brilliant as a quasar, but it is the closest active galaxy to Earth. This large elliptical galaxy recently swallowed a smaller spiral, whose remains appear as dark dust lanes. The merger funneled huge quantities of gas into Centaurus A's core, where it feeds a supermassive black hole. As the black hole accretes the gas, some of the material is blasted out of the galaxy in powerful outflows (green).

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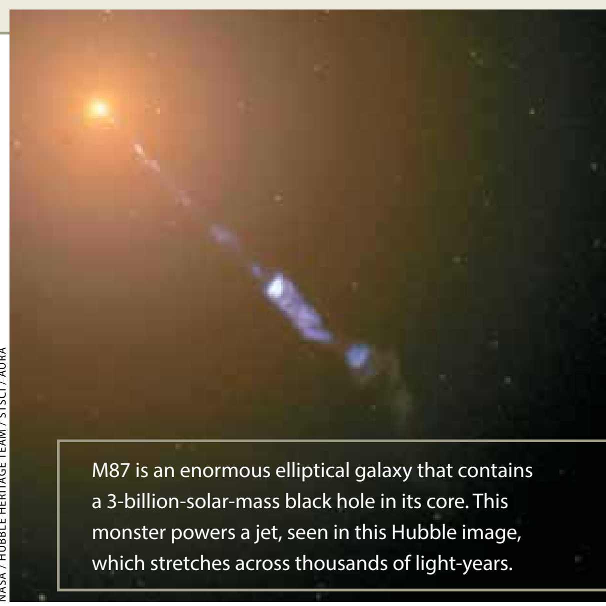
A Quasar in *Every* Galaxy?

By Robert Irion

FOR EVERY SUPERSTAR in the Hollywood firmament, thousands of pedestrian actors just try to make ends meet. Likewise, for every brilliant quasar that illuminates the universe, countless other galaxies — like our Milky Way — shine with the unspectacular light of middle age.

But the steady glow of galaxies doesn't tell the whole story. Several lines of research now suggest that nearly all mature star cities threw tantrums in their youth. At least once in every major galaxy's history, radiation blazed from hot matter accreting violently onto a supermassive black hole in the core. Astronomers think these quasar-like outbursts were relatively brief. Even so, they determined the fates of the graceful galaxies we see today.

Theorists and observers reached this conclusion by focusing on the early epochs when ravenous black holes gobbled most of their mass. Ironically these black holes limited their own growth by unleashing torrents of energy that drove away the surrounding gas (*S&T:* April 2005, page 42). These waves of unrest also dictated the ebb and flow of starbirth in the host galaxies. This feedback process forged a close link between massive black holes and their surrounding stars.

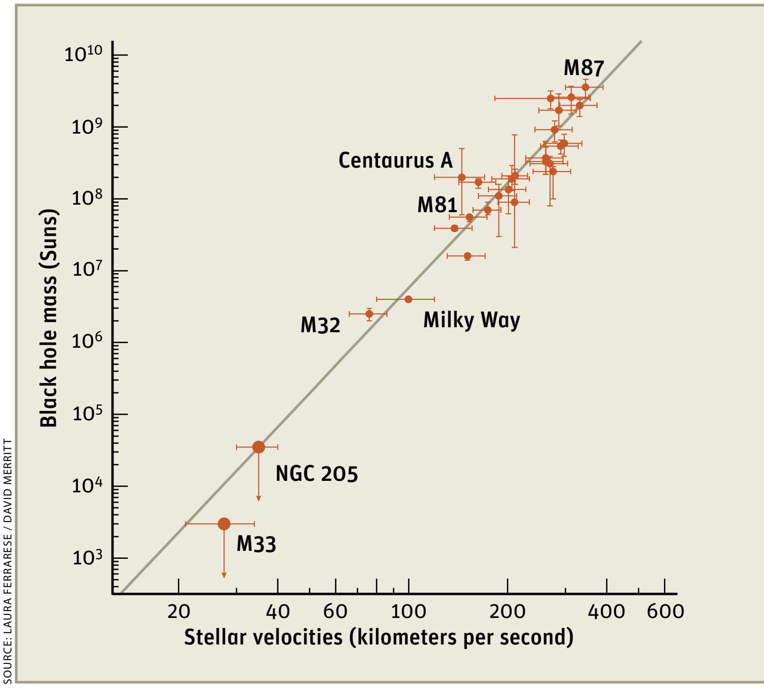


NASA / HUBBLE HERITAGE TEAM / STSCI / AURA

M87 is an enormous elliptical galaxy that contains a 3-billion-solar-mass black hole in its core. This monster powers a jet, seen in this Hubble image, which stretches across thousands of light-years.

This view of abrupt but dazzling mayhem in major galaxies represents a profound conceptual shift in our understanding of cosmic evolution. Long ago astronomers grew accustomed to a universe with extreme ranges of behaviors. Stately spirals like the Milky Way and Andromeda seemed normal; quasars and other types of active galaxies, such as blazars and Seyfert galaxies, were the freaks. But researchers now regard the freaks as unusual only in the time domain. It's all a matter of *when* in their evolution we happen to see them.

"Quasars appear rare because they are suicidal," says Abraham Loeb (Harvard-Smithsonian Center for Astrophysics). "They accrete a lot of gas, then they shut themselves off. On cosmological time scales, it's just like an explosion." The Milky Way's core certainly erupted in this way before settling down. But even at its peak vigor, our galaxy didn't hold a candle to the quasars raging in the far reaches of the universe.



SOURCE: LAURA FERRARESE / DAVID MERRITT

Black Holes Everywhere

With luminosities that often exceed that of the billions of stars in their host galaxies, quasars are the most energetic members of a class known as active galactic nuclei, or AGN. Quasars can shine so brightly only by devouring huge quantities of gas — enough to build black holes packing hundreds of millions to billions of solar masses. Our Milky Way, by contrast, hosts a modest central black hole containing "only" about 4 million solar masses.

Direct observational evidence of these monster black holes first surfaced in the 1990s, when the Hubble Space Telescope probed the cores of 40 nearby galaxies. Hubble's spectrograph revealed pronounced Doppler shifts, clear signs that stars at the very center of almost every observed galaxy whirl at breakneck speeds toward us on one side and away from us on the other. The rapid stellar orbits indicated deep gravitational fields carved by supermassive black holes.

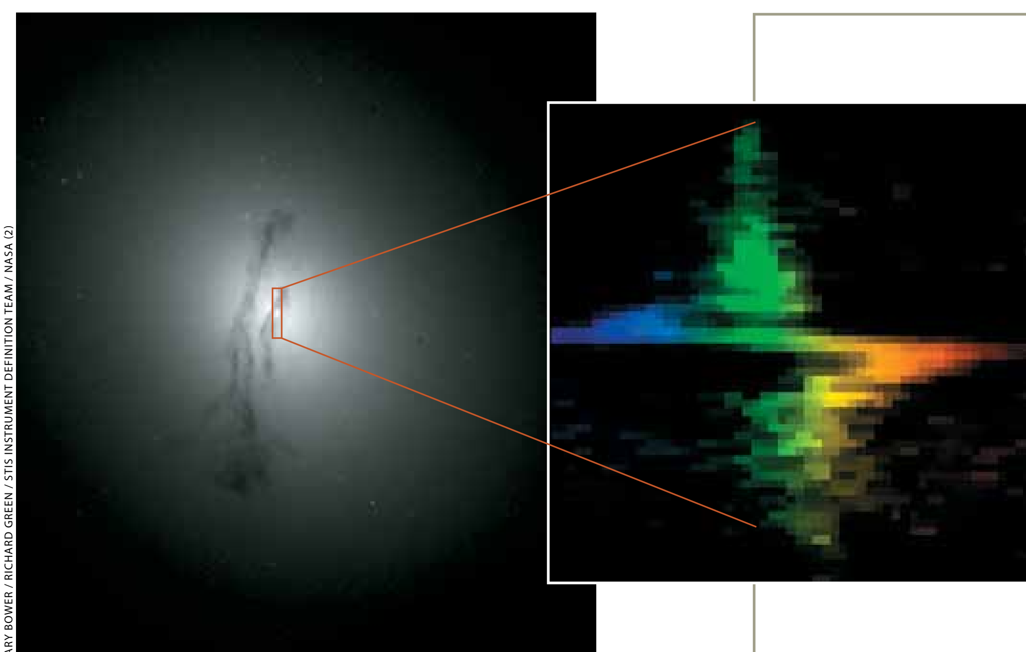
The results of Hubble's survey surprised even the observing team. "At the beginning I thought black holes were rare, maybe 1 galaxy in 10 or 100," says Douglas Richstone (University of Michigan, Ann Arbor). "Now we've shown they are standard equipment."

There is one key caveat, however. Only galaxies with a central bulge host a monster black hole. Bulges are the nearly spherical swarms of old stars that surround the cores of most large galaxies. But as many as 15% of spiral galaxies consist only of starry disks, with no bulge whatsoever. The face-on spiral M33 in Triangulum is a nearby example. "It has no bulge and no black hole that we can detect," says Richstone.

Still, most large galaxies follow a remarkable trend. In 2000 teams led by Karl Gebhardt (University of Texas, Austin) and Laura Ferrarese (Rutgers University) showed that the masses of black holes inside galaxy cores correlate very strongly with the velocities of stars orbiting through their host bulges. A higher bulge mass produces faster stellar orbits, on average. And the researchers found that the higher the bulge mass, the higher the mass of the central black hole.

This landmark discovery, called the *M-sigma relation,** catalyzed the field. It provided compelling evidence that central black holes are intimately connected to the evolution of their host galaxies. Most astronomers had suspected that galaxies and their black holes grew simultaneously during periods when they accreted lots of gas, possibly during galaxy mergers. "To me, the M-sigma relation made the physi-

* *M is the mass of the central black hole, and sigma (σ) is the velocity dispersion of the bulge, a measure of how fast its stars are moving.*


GARY BOWER / RICHARD GREEN / STIS INSTRUMENT DEFINITION TEAM / NASA (2)

The Hubble Space Telescope imaged the core of M84, a giant elliptical galaxy in the Virgo Cluster. The orange rectangle indicates the nuclear region observed by Hubble's imaging spectrograph, which measured the velocities of gas near M84's center and found a zigzag pattern (inset) indicating extremely fast orbital motions. The gas orbits at speeds of 400 kilometers per second within 26 light-years of the center, indicating an invisible mass equal to 300 million Suns.

Using Hubble and other instruments, astronomers surveying dozens of galaxies have found a remarkable fact: The mass of the central supermassive black hole correlates with overall stellar velocities in the galaxy's spheroidal component (either an entire elliptical galaxy or the central bulge of a spiral galaxy). These velocities, in turn, correlate with the mass of the spheroidal component. The discovery of this "M-sigma relation" told astronomers that the evolution of black holes and their host galaxies is intimately connected.

cal connection clear," says Megan Urry (Yale University). "All galaxies with supermassive black holes must have gone through this active phase."

The tightness of the M-sigma relation amazed theorists as well. "It's almost magical, because the scales are so completely different," says Nickolay Gnedin (University of Colorado, Boulder). "If you draw a galaxy on a sheet of paper, the central black hole would be the size of an atom. It's hard to understand how the black holes know about the galaxies, or how the galaxies know about them." But observers and theorists are converging on an explanation.

Active Galaxies Near and Far

To understand the feedback processes at work in galaxies, astronomers use deep surveys at various wavelengths to trace black-hole activity across billions of years. In visible light the ongoing Sloan Digital Sky Survey has played a pivotal role. Its 3.5-meter (140-inch) telescope in New Mexico has detected about 70,000 quasars. Each quasar's spectrum reveals how much its light has been redshifted by cosmic expansion, which astronomers convert into the age when the quasar was active.

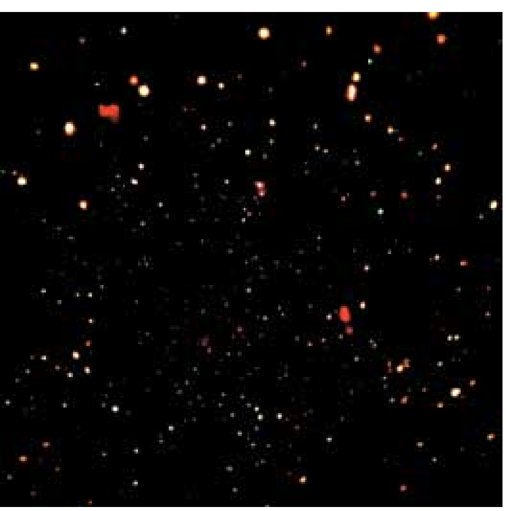
Some of the most powerful known quasars arose earlier than a redshift of 6, which translates to 1 billion years after the Big Bang. The most distant quasar, at redshift 6.42, lived at a cosmic age of only 870 million years. "These are among the most luminous objects the universe has ever seen," says Xiaohui Fan (University of Arizona, Tucson). Theorists think these blazing objects arose in special places where matter concentrated most densely in the wake of the Big Bang. Seed black holes of a few thousand solar masses — created by an as-yet unknown process — accumulated those titanic masses by devouring gas and other black holes. But those intensely luminous quasars were rare. So far Sloan has imaged just 19 such objects with redshifts of 6 or higher.

In a universe of hundreds of billions of galaxies, the 70,000 Sloan quasars seem like a drop in the bucket. Fortunately, other eyes on the sky are finding more. Quasars spew copious X-rays as million-degree gas spirals toward the supermassive black hole. NASA's Chandra X-ray Observatory has exposed those fiery pinpricks with a narrow, deep survey in each hemisphere. Whereas the Sloan survey sees about 10 quasars per square degree, Chandra's exposures reveal 7,000 active galaxies in the same area. "At high redshifts we find active galaxies up to 100 times less luminous than the rare powerful Sloan quasars," says Niel Brandt (Penn State University). "These are the typical active galactic nuclei in the universe."

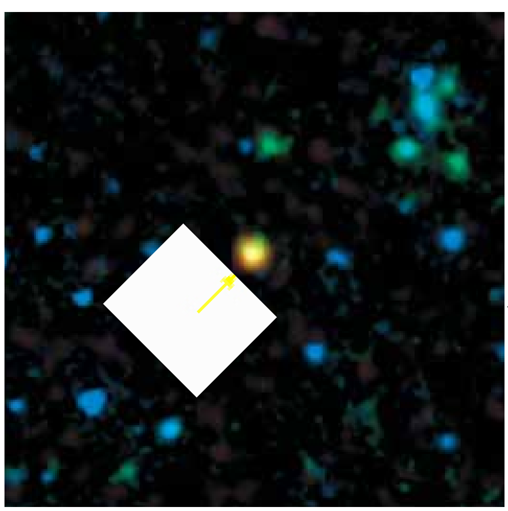
When Brandt extrapolates Chandra's detections to the rest of the sky, he calculates that the observatory can see the cores of 5% of all "decent-size" galaxies in the universe. That's a plausible statistic, says Brandt, because astronomers think the cores of major galaxies light up as X-ray-bright AGN just a small fraction of the time. Moreover, Chandra may miss galaxies so choked by thick clouds of gas and dust that X-rays cannot escape efficiently.

Fortunately, NASA's infrared Spitzer Space Telescope, launched in August 2003, can detect some of these hidden AGN. Infrared light can stream through the dense toruses thought to shroud some of the most vigorously accreting galaxy cores. In 2005 two teams of researchers reported that Spitzer finds the glowing cores of active galaxies everywhere it looks,

Left: A 23-day Chandra deep exposure in Ursa Major reveals hundreds of point sources in an area about 60% the size of the full Moon. Most are very distant supermassive black holes gobbling up enormous quantities of gas and shining as active galactic nuclei. Center: With its ability to peer through dust, NASA's infrared Spitzer Space Telescope has revealed thousands of active galactic nuclei previously hidden by gas and dust, such as the quasar in Draco shown in this composite Spitzer and radio image. Right: The Sloan Digital Sky Survey captured this quasar with a redshift of 6.4 (arrowed) in Ursa Major.



NASA / CXC / PSU / DAVID ALEXANDER & OTHERS

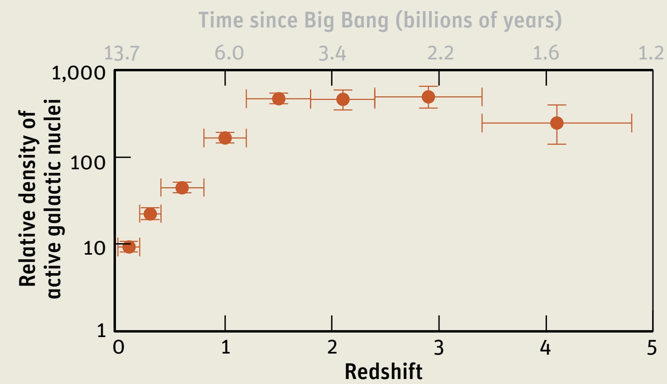


NASA / JPL / CALTECH / ALEJO MARTÍNEZ SANSIGRE

SDSS COLLABORATION / XIAOHUI FAN

especially between redshifts of 2 and 1 (roughly 3 billion to 6 billion years after the Big Bang) — the epoch when most galaxies assembled. "Most quasars at these redshifts and beyond are hidden behind gas and dust," says Urry. "That makes sense. As those galaxies are collapsing, they should be in the messiest, dirtiest environments."

One recent study combined optical and X-ray observations of dusty galaxies and their central black holes. David Alexander (Cambridge University, England) and his colleagues examined 20 "submillimeter" galaxies around redshift 2. These luminous galaxies were originally spotted by the 15-meter James Clerk Maxwell Telescope at Mauna Kea, Hawaii, which can detect submillimeter waves radiating from dusty stellar nurseries. An optical study led by Scott Chapman (Caltech) showed that these galaxies create about one new star every day — 100 times higher than the Milky Way's rate. Chandra X-ray data revealed that 15 of the 20 submillimeter galaxies have black holes actively feeding on gas.



This graph shows the relative cosmic density of active galactic nuclei (those with average luminosities) by redshift. Quasars were much more common in the distant past, meaning that supermassive black holes accumulated most of their mass long ago and have largely settled down to a state of quiescence.

SOURCE: GÜNTHER HASINGER (MPI) & OTHERS

"These galaxies are forming a lot of stars, and at the same time you have almost continual black-hole growth," says Alexander. "We're seeing the construction of massive galaxies and their central black holes." The team claims that this is the first solid evidence of how the mysterious M-sigma relation arose. Alexander thinks the submillimeter galaxies eventually became titans like M87 — a nearby giant elliptical galaxy in the Virgo Cluster whose 3-billion-solar-mass black hole propels a jet to near-light speed.

Models of a Violent Universe

This flurry of multiwavelength observations gave theorists what they needed to construct more accurate models of galaxy growth. By mid-2005 the consensus was clear: Massive black holes control the evolution of every major galaxy.

Black holes can't do it in isolation, however. A lone galaxy with a black hole at its heart will happily swirl for eons, and the hole will eat only what happens to drift nearby. To trigger rabid growth spurts, a black hole needs a major disturbance to funnel torrents of fresh gas into the core.

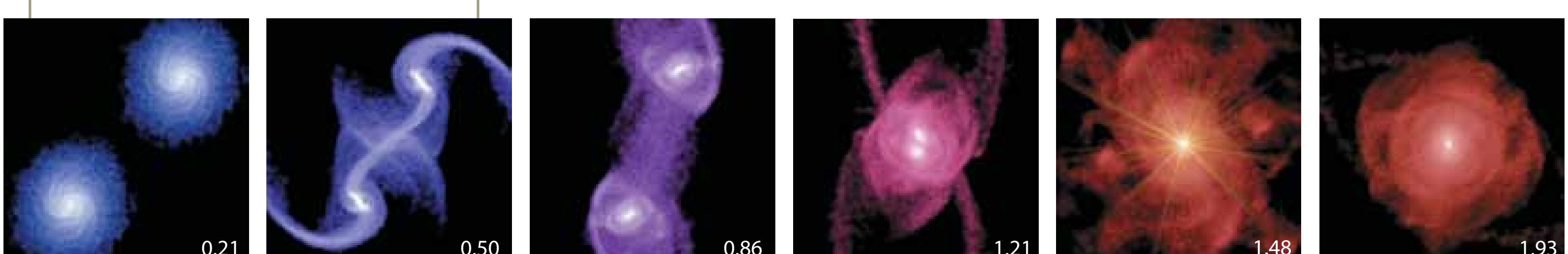
Collisions between gas-rich galaxies do the trick, a view supported by a model created by Philip Hopkins and Lars Hernquist (both at the Harvard-Smithsonian Center for Astrophysics) and their coworkers. Telescopes reveal galaxy mergers everywhere, but they were far more common in the early universe, when galaxies were closer together. To find out how these crashes affected the black holes and the internal dynamics of galaxies, the team created computer simulations that varied the galaxy masses, gas contents, and collision angles.

The results, published in March 2006, produced a new insight. "The evolution of quasars is more complicated than people assumed," says Hernquist. "Their activity is sporadic, and they are visible as intense sources only for very short periods." The simulations suggest that a black hole accumulates most of its mass in extreme feeding episodes — triggered by mergers — that switch on a bright quasar for just 1% of a galaxy's existence. For the rest of its lifetime, the nucleus is mostly dormant.

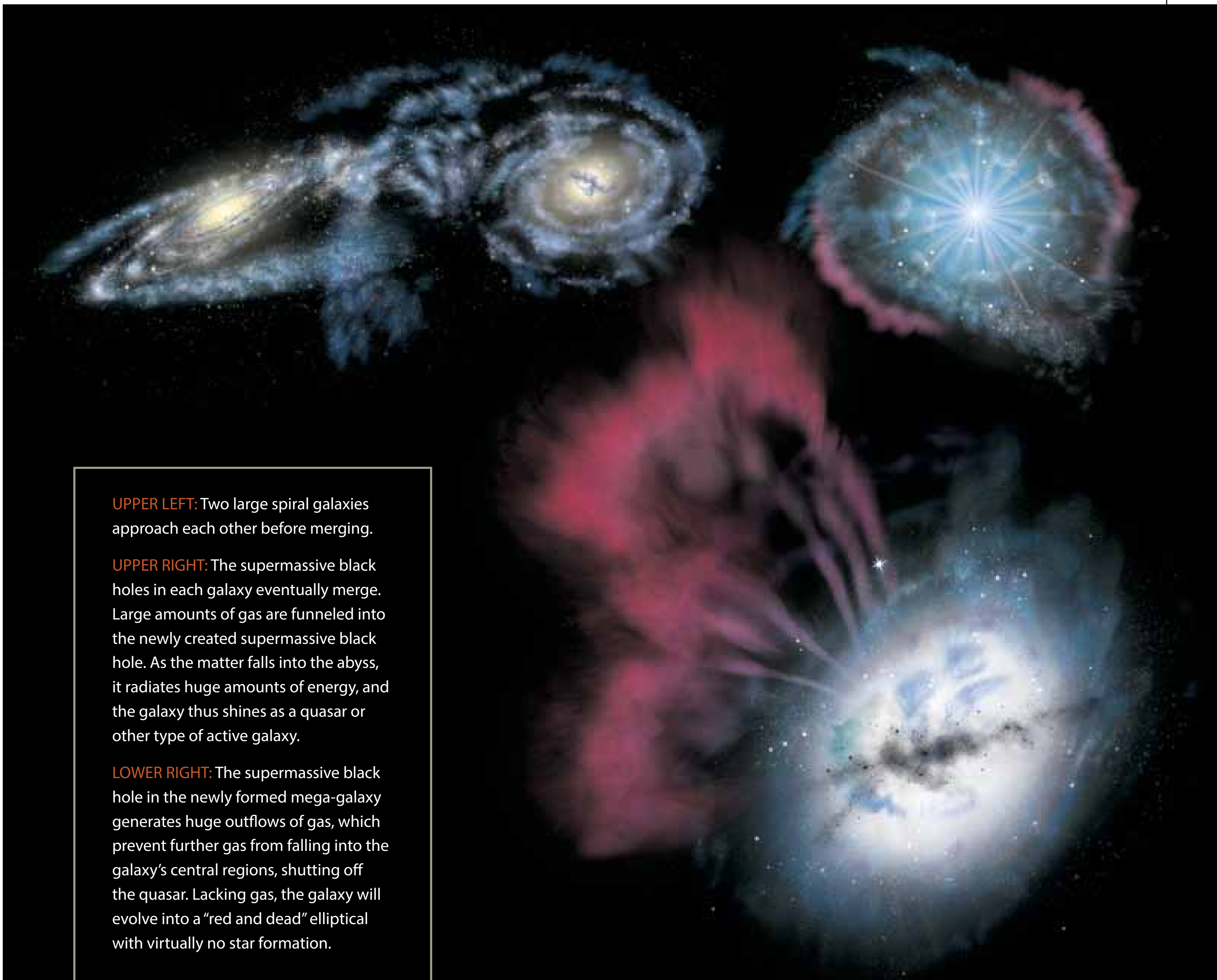
Observations support this scenario. A team led by Charles Steidel (Caltech) reports that ordinary galaxies at redshifts of 2 to 3.5 are 50 times more common than quasars during that era — just as one would expect for a population of mostly quiescent black holes.

In this new picture, black holes and galaxy bulges form together in a sudden, violent "blowout phase" triggered by a merger. The impact on the surrounding galaxy is profound. Energy released by matter plunging toward the black hole ignites the quasar and heats gas throughout the galaxy's core. But the gas can only take so much heat

This supercomputer simulation depicts two spiral galaxies merging to form an elliptical. Each frame is about 300 million light-years across. The number in each frame represents the amount of cosmic time (in billions of years) since the simulation began. When two galaxies collide, their central black holes accrete huge quantities of gas and eventually merge (at a time of 1.48 billion years as simulated here). The galaxy thus shines brightly as a quasar for a brief period of time. In the fourth frame, the black holes are blowing out large amounts of gas.



PHILIP HOPKINS / LARS HERNQUIST / VOLKER SPRINGEL (6)



S&T: GREGG DINDERMAN

UPPER LEFT: Two large spiral galaxies approach each other before merging.

UPPER RIGHT: The supermassive black holes in each galaxy eventually merge. Large amounts of gas are funneled into the newly created supermassive black hole. As the matter falls into the abyss, it radiates huge amounts of energy, and the galaxy thus shines as a quasar or other type of active galaxy.

LOWER RIGHT: The supermassive black hole in the newly formed mega-galaxy generates huge outflows of gas, which prevent further gas from falling into the galaxy's central regions, shutting off the quasar. Lacking gas, the galaxy will evolve into a "red and dead" elliptical with virtually no star formation.

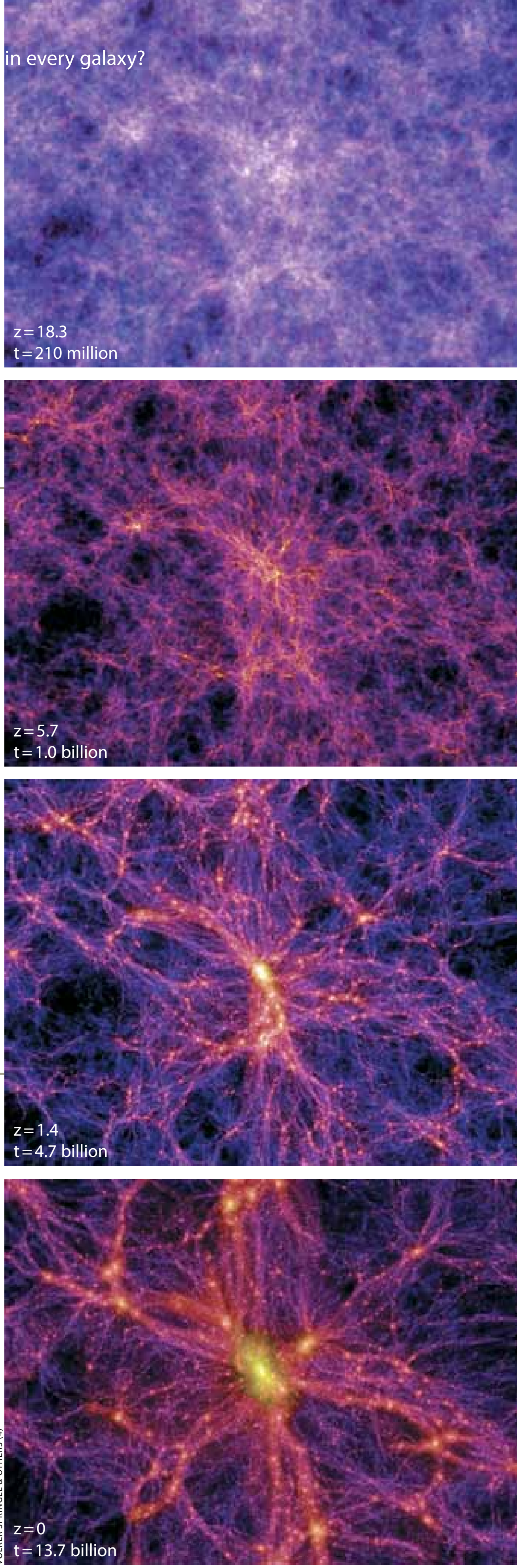
before it all escapes, like water from a boiling pot. Bigger galaxies have enough gravity to hold onto hotter gas, so the black hole grows even more massive.

Astrophysicists think this explains why small galaxy bulges host small black holes, while big bulges host big black holes. "There is a critical point in the growth of black holes when they drive away gas," says Hernquist. The outpouring of energy stunts both the black hole's growth and star formation in the galaxy's bulge, in lockstep — leading to the M-sigma relation. Leftover gas then settles down into a disk of stars that resembles today's spirals.

To view animations of galaxy mergers and activity associated with supermassive black holes, visit SkyandTelescope .com/quasar

This furious feedback was a crucial component of the Millennium Run, a simulation of the largest virtual volume of space ever attempted. A team led by Volker Springel (Max Planck Institute for Astrophysics, Germany) simulated the way in which matter clumped together inside a cube that is more than 2 billion light-years on a side. The team started with the tiny fluctuations in the distribution of matter encoded in the subtle temperature fluctuations of the cosmic microwave background. When gravity and dark energy acted on those fluctuations for the simulated age of the universe, the result was a delicate network of galaxy clusters — the familiar cosmic web (see page 24).

The Millennium Run incorporated feedback within and among galaxies, such as supernova winds and powerful jets of radio-emitting gas from supermassive black holes. The resulting shock waves dictated the fate of every galaxy. The simulation produced giant early galaxies with Sloan-type quasars, but outflows from the black holes soon blasted away the surrounding gas. These gargantuan black holes now reside within the "red and dead" giant elliptical



VOLKER SPRINGEL & OTHERS (4)

These frames from the Millennium Run supercomputer simulation suggest how the cosmos evolved over billions of years. (The letter z denotes redshift, and t is time elapsed in years since the Big Bang.) The gravitational pull of dark matter helps galaxies collect in long filaments of enhanced density surrounding enormous, low-density voids — the cosmic web. By incorporating feedback loops with quasar-like activity, the simulation produced galaxies that closely resemble the ones we see today.

galaxies (like M87) at the centers of today's richest clusters.

On the low-mass end, supernovae in simulated dwarf galaxies disrupted star formation, transforming many of these objects into barely visible nuggets of mostly dark matter like certain dwarfs seen in our Local Group (*S&T:* July 2005, page 16). These galaxies lack organized cores and most likely don't contain central black holes. No quasars or active nuclei ever illuminated these small, quiet islands, which greatly outnumber major galaxies like ours.

Our Bright Destiny

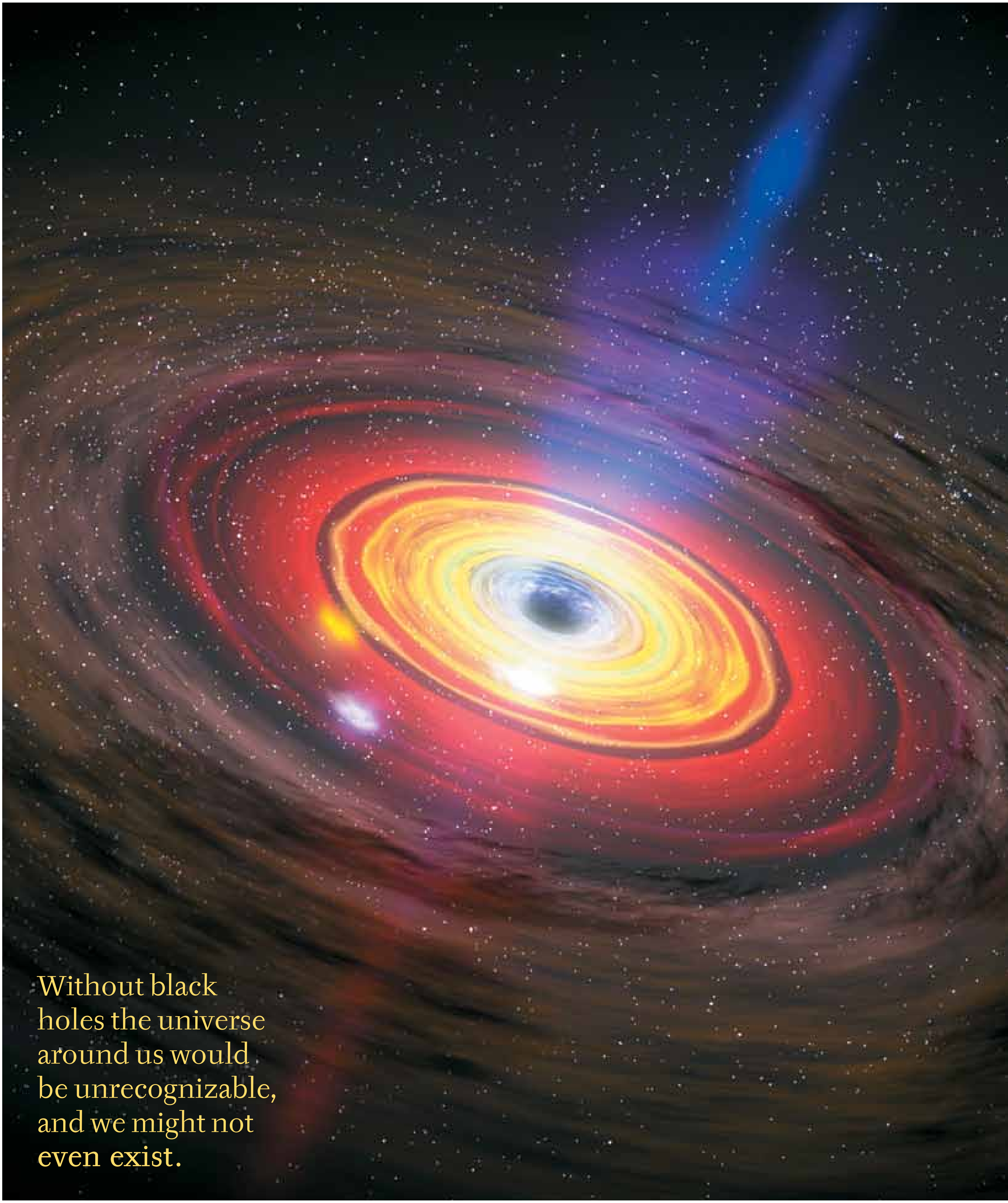
Compared to brilliant galaxies elsewhere, the Milky Way's core is anemic. Our galaxy has a spheroidal bulge of old stars, indicating that it went through at least one major merger. But its modest black hole suggests that even during that merger, the core never blazed like the quasar beacons seen by the Sloan survey.

According to radio and X-ray data, our galaxy's supermassive black hole currently swallows just 1/100,000 of the gas around it. The gas's emitted energy is so feeble that telescopes can detect it only because the black hole resides in our cosmic backyard. Simulations by Fulvio Melia (University of Arizona, Tucson) and others show that this situation won't change anytime soon. "It would take something really dramatic to churn the gas where it leads to a hyperinflow," he says.

But something dramatic looms in the distant future. The Milky Way and the relatively nearby Andromeda Galaxy (M31) are on a collision course, with a merger inevitable in several billion years (see page 108). The interaction will funnel streams of new gas into the core of the combined supergalaxy — where the two existing black holes will coalesce. (M31 boasts a central black hole roughly 10 times as massive as ours.) Calculations by Hernquist and Melia suggest that the revitalized black hole could accrete 1 to 10 solar masses of gas per year, eventually growing to at least 100 million solar masses.

In a darkening universe of galaxies accelerating ever farther apart, the crash will light up our neighborhood. "It will appear as a quasar from the outside," Melia says. But the display will carry a cost. Both M31 and the Milky Way of our descendants will forfeit their stately spiral configurations to create an undistinguished elliptical blob. ✴

Freelance journalist Robert Irion *lives in Santa Cruz, California, and covers astrophysics for* Science. *He writes his articles during periods of intense activity, separated by disturbingly long intervals of quiescence.*



NASA / DANA BERRY / SKYWORKS DIGITAL

How Black Holes *Helped Build the* Universe

● By CHRISTOPHER WANJEK

Add up all the light from all the stars at all wavelengths and you'll find that this grand total is only modestly more energy than that of the electromagnetic radiation produced by matter being torn to shreds around black holes.

The ultimate behind-the-scenes players, black holes by definition do not emit light. But somehow they are the source of up to a fifth of the universe's luminous energy. The mechanism for this terrific outpouring of light is a phenomenon called *accretion.* Matter lured by a black hole's extreme gravity settles into an accretion disk. Near the black hole, where gravity is most intense, disk material is heated to hundreds of millions of degrees and radiates brilliantly before it falls in.

Contrary to public perception, black holes have a difficult time swallowing matter. Material that comes near a black hole wants to orbit the beast, not fall in. The difference between black holes and other massive objects, such as stars, is that once matter falls into a black hole, it can't get out.

Only in the past few years have scientists begun to understand that black holes, through accretion, serve as chief architects for the universe. Accretion is not just a one-way ticket to the netherworld. Matter pours into the black hole, but a similar amount violently flies *away.* All of this energy — gravity, light, and motion — triggers star formation, makes or breaks galaxy formation, and redistributes heavy elements in such a way that, quite possibly, enables planet formation and life itself. "Without black holes the universe would look quite different," says Richard Mushotzky (NASA/Goddard Space Flight Center).

Despite the fact that black holes are an important source of light and motion in the universe, only the most rudimentary aspects of their accretion process are well understood: Matter goes in, and energy comes out. The deception begins with our simplistic concept of black holes. They're just holes in outer space down which hapless matter falls, right? Whirlpools of spacetime. Cosmic vacuum cleaners. Resistance is futile. If only it were that straightforward.

As Mushotzky points out, "It's hard to throw something down a black hole." Basic physics can't explain how matter ever reaches an event horizon, the theoretical border around a black hole from beyond which nothing can escape. Angular momentum, for one, tries to make sure nothing gets too close to a black hole. Imagine yourself on a rapidly spinning merry-go-round: If you don't hold on to a pole, you'll fly outward. Matter whipping around a black hole is subject to this same centrifugal force.

Consider quasars: bright galaxy cores powered by supermassive black holes that can shine more brightly than a trillion Suns. For accretion to produce the light energy associated with these extraordinary objects, gas must shed copious amounts of angular momentum before it can venture closer to the black hole to liberate its gravitational energy. The black hole's gravity cannot do it alone.

Explaining the tremendous light output from accretion is not difficult. Although other processes are also involved, most of the luminosity comes from friction. Electrons and ions whirl around the disk close to the speed of light, and as they collide with one another and cool, they emit electromagnetic radiation at many different wavelengths. Rotational energy is thus converted into thermal energy.

Astronomers don't yet understand how black-hole accretion produces jets and winds escaping into intergalactic space. "A tremendous amount of energy is released through accretion," says Christopher Reynolds (University of Maryland, College Park). "Not to understand the channel through which all this energy flows is, well, embarrassing."

The Ins and Outs of Accretion

Disks are everywhere, so it shouldn't be surprising that accretion disks exist around black holes. Earth and our neighboring planets formed from a disk that encircled the Sun some 4.6 billion years ago. Our galaxy, too, has a flat disk containing billions of stars. Nature likes to form disks; it's what happens when rotating gas clouds collapse gravitationally.

Yet two roadblocks arise when the discussion turns to *black-hole* accretion disks: They are so small that they're extremely difficult to observe in detail, and their energy output cannot be explained with simple physics.

The first serious theoretical work to explain black-hole accretion came in the late 1960s, when Soviet physicists Nikolai Shakura and Rashid Sunyaev put forth a simple theory of turbulence. Water forced to flow too quickly down a pipe becomes turbulent and chaotic. Accretion-disk gas might work the same way, they argued, such that turbulence would create friction, slow gas rotation, and cause the gas to spiral toward the black hole. Unfortunately, the expected amount of disk turbulence is several orders of magnitude too small to explain the observed accretion energy.

Three decades followed with few theoretical or observational advances. A major breakthrough finally came in 1991, when Steve Balbus and John Hawley (University of Virginia) realized that magnetic fields threading an accretion disk energize the system. "Even a weak magnetic field can do the job," says Hawley.

Their theory, called magnetorotational instability (MRI), states that gas entering an accretion disk can maintain some of the magnetic field it had when it was part of a star. That weak field can perturb the disk, creating instability and amplifying the magnetic field, which produces turbulence of the order hoped for by Shakura and Sunyaev. "Turbulence transfers angular momentum like a conveyor belt to the outer disk, while material in the inner disk moves closer to the black hole," says Reynolds.

The theory was not entirely new; Balbus and Hawley independently rediscovered an idea buried in a 1961 tome by legendary astrophysicist Subrahmanyan Chandrasekhar. Soviet researcher Evgeny Velikhov had also studied this type of magnetic instability in the late 1950s. This time MRI stuck, and Balbus and Hawley continue to perfect it today with simulations on high-end computers. With Jim Stone (Princeton University) and others, the theorists are attempting to reproduce realistic flows across the entire accretion disk in three dimensions. Some scientists liken the development of MRI to grasping fusion in stars nearly a century ago.

The same accretion-disk physics should apply to all black holes, regardless of size. So to test their ideas, scientists can study powerful but distant supermassive black holes in the nuclei of active galaxies or study less powerful but closer stellar-mass black holes in our Milky Way.

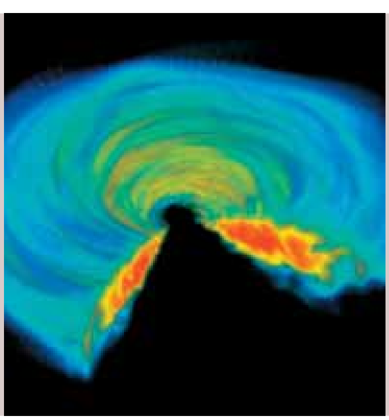
A team led by Jon Miller (University of Michigan) turned to GRO J1655–40, a stellar-mass black hole only 10,000 light-years away. Using the Chandra X-ray Observatory, Miller and his colleagues discovered an X-ray-absorbing wind of hot, highly ionized gas. As they reported in *Nature* for June 15, 2006, detailed spectral analysis ruled out thermal and radiation pressure, two common means for driving a wind, leaving magnetism as the only viable force to lift gas from the disk and send it flying outward. "This demonstrates that disk accretion onto black holes is a fundamentally magnetic process," says Miller.

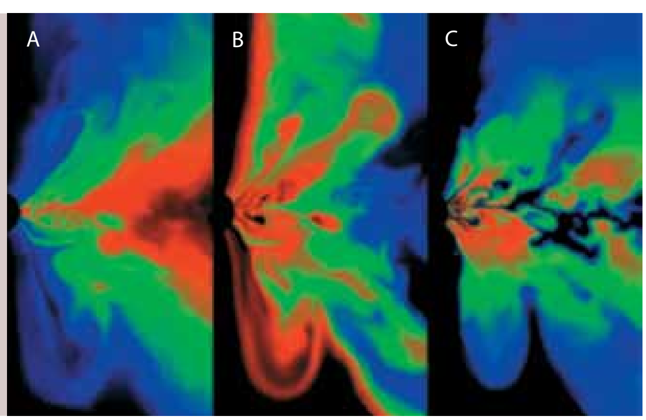
This Chandra observation offers the best support yet for MRI. But there's still work to do. The effects of black-hole spin and particle outflows in winds and jets are just now being folded into the MRI paradigm. And it is the outflows that hold significant influence over the formation and evolution of stars and galaxies.

Blowing in the Wind

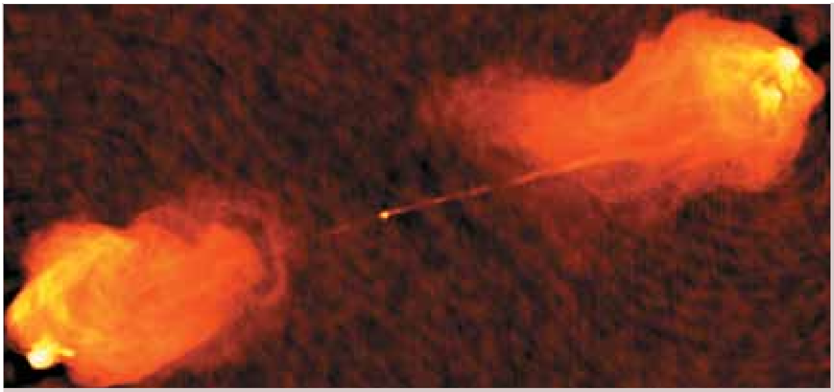
In April 2006 a team led by Steve Allen (Stanford University) and Chris Reynolds estimated that quasars can be up to 20% efficient in converting matter into energy via Einstein's equation $E = mc^2$. Nuclear fusion, in contrast, is only about 1% efficient. Most of that quasar energy goes

Right: This image comes from a three-dimensional simulation of an accretion disk surrounding a black hole. Magnetic fields generate turbulence in the disk, which robs material of angular momentum, causing it to spiral inward. Far right: These computer-animation frames depict a snapshot of the density (A), heat (B), and magnetic pressure (C) in the inner 10% of an accretion flow.


JOHN HAWLEY

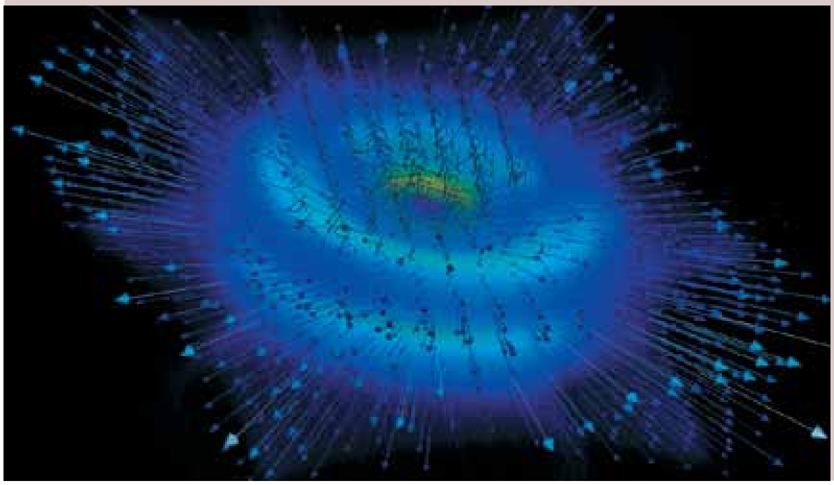


JIM STONE (3)



NRAO / AUI

This radio image of the galaxy Cygnus A shows two jets composed of electrons and protons shooting away at near-light speed from a supermassive black hole and spanning 300,000 light-years of space in each direction. The particles are eventually trapped by the galaxy's magnetic field, forming the lobes at the far right and left. The image starkly demonstrates a black hole's ability to blow out material and affect its surroundings at immense distances.



DANIEL PROGA

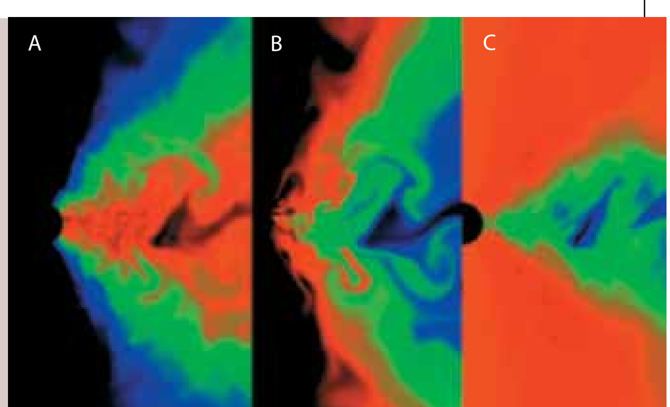
This computer-simulation frame shows a powerful wind of gas emanating from the inner region of a black-hole accretion disk. The sheer photon pressure of the disk's radiation drives the wind, which can attain speeds up to 20% that of light. The amount of escaping matter can equal the amount falling into the black hole.

into jets, which are particle streams shooting away from the black hole perpendicular to the accretion disk nearly at light speed, extending for tens of thousands or even hundreds of thousands of light-years. There are many viable hypotheses for how these jets form, but we don't know if any are correct. Nevertheless, the ubiquity of jets provides evidence of something that computer simulations have also found: Black holes help shape the universe.

Simulations by Simon White (Max Planck Institute for Astrophysics, Germany) and others start with the latest data on the cosmic microwave background, the Big Bang's afterglow. Then they add gravity and watch the universe grow. With gravity alone, the simulations create 100 times more galaxies than what we see today. "There are too many, too early, too bright, and too big," says Mushotzky. When theorists add the impact of star formation to the simulation, not much changes. But when they include black-hole accretion, the simulations match observed cosmic structure much better. This correlation implies that massive black holes, long thought to merely pull matter in and aid in galaxy formation, actually stunt their growth through accretion outflows (*S&T:* July 2006, page 40).

Accretion-disk winds, like jets, can blow material out of galaxy centers, choking off star formation and removing the fuel supply for the wind itself. Winds are now readily detected in the vicinity of accretion disks, and their impact is just being appreciated. Some, according to Sarah Gallagher (University of California, Los Angeles), are blowing away

When a stellar-mass black hole has a minimal amount of material to swallow, a process known as advection-dominated accretion flow (ADAF) might take over. The gas enters the black hole so quickly that it can't cool off, so the system appears quiescent. These 2-D computer-animation frames show that the material enters the black hole from all directions. Strong convective eddies transport mass inward and outward, but the net accretion rate is very small and is determined by the properties of the flow near the black hole. A: Red shows where the gas density is highest, blue the lowest. B: Red represents the hottest gas, blue the coolest. C: Red highlights material that is orbiting fast and flowing outward; blue marks material that is orbiting slow and falling inward.



JIM STONE

from the black hole at more than 20% light speed, as measured from blueshifted absorption lines. The winds contain carbon, nitrogen, and silicon. They could be an efficient means of injecting such elements into the intergalactic medium. This, too, would have broad implications for galaxy evolution, star formation, and even the origin of life.

Like jets, winds are difficult to explain, especially when the gases are not ionized, which means atoms are not easily influenced by magnetic fields. Miller found evidence of magnetic fields helping to drive a highly ionized wind in stellar-mass systems. But what about the beasts in galaxy cores? Daniel Proga (University of Nevada, Las Vegas) and his colleagues have studied the role of magnetic fields, radiation pressure, and radiation heating in driving a wind. For supermassive black holes, their computer simulations demonstrate that the sheer pressure of an accretion disk's radiation could propel weakly or moderately ionized gas to high speeds; the electrons serve as sails. Too many X-rays will overionize atoms, ripping the sails and thus preventing a wind. But X-ray-absorbing gas near a black hole can shield gas farther away and prevent overionization, allowing the winds to gather speed from the outer disks.

Feeding the Beast

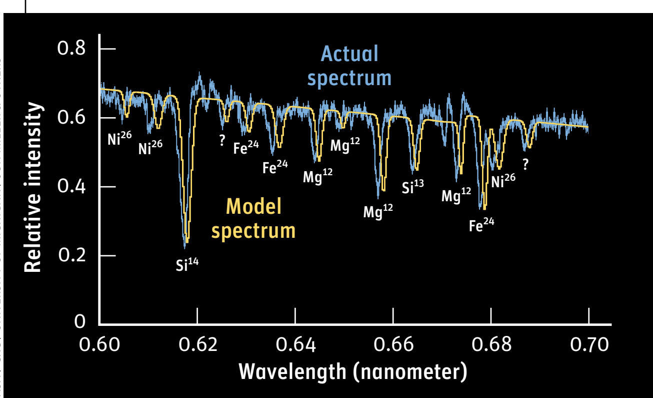
Proga asks another key question: "Why are some systems better than others at accretion?"

The supermassive black hole in our galaxy's core, called Sagittarius A* (pronounced "A star"), is an instructive example. It is about a billionth as luminous as a quasar, yet its fuel supply is only a factor of about 1,000 less. Since there's fuel to make it brighter, something in addition to MRI must be at play. Enter the advection-dominated accretion flow (ADAF). According to the ADAF model, championed by Ramesh Narayan (Harvard-Smithsonian Center for Astrophysics) and others, when there is little accretion, the disk gas enters the black hole very quickly. The gas gets very hot but is unable to cool; the heat energy is almost entirely lost to the black hole, so the luminosity is minimal. This model works well for quiescent stellar-mass black holes, but some scientists question its feasibility for the monsters in galaxy cores.

At the high end of the luminosity scale, galaxy mergers and star formation can stir up activity by nudging gas toward a supermassive black hole. Galaxy mergers disrupt angular momentum and send stars off on new trajectories, often toward the core. Mergers also spur star formation, and young massive stars have fierce particle winds that can feed a hungry black hole. When these stars go supernova, which they do relatively quickly, they provide raw material for a centrally located accretion disk, as well as shock waves to shove material in that direction.

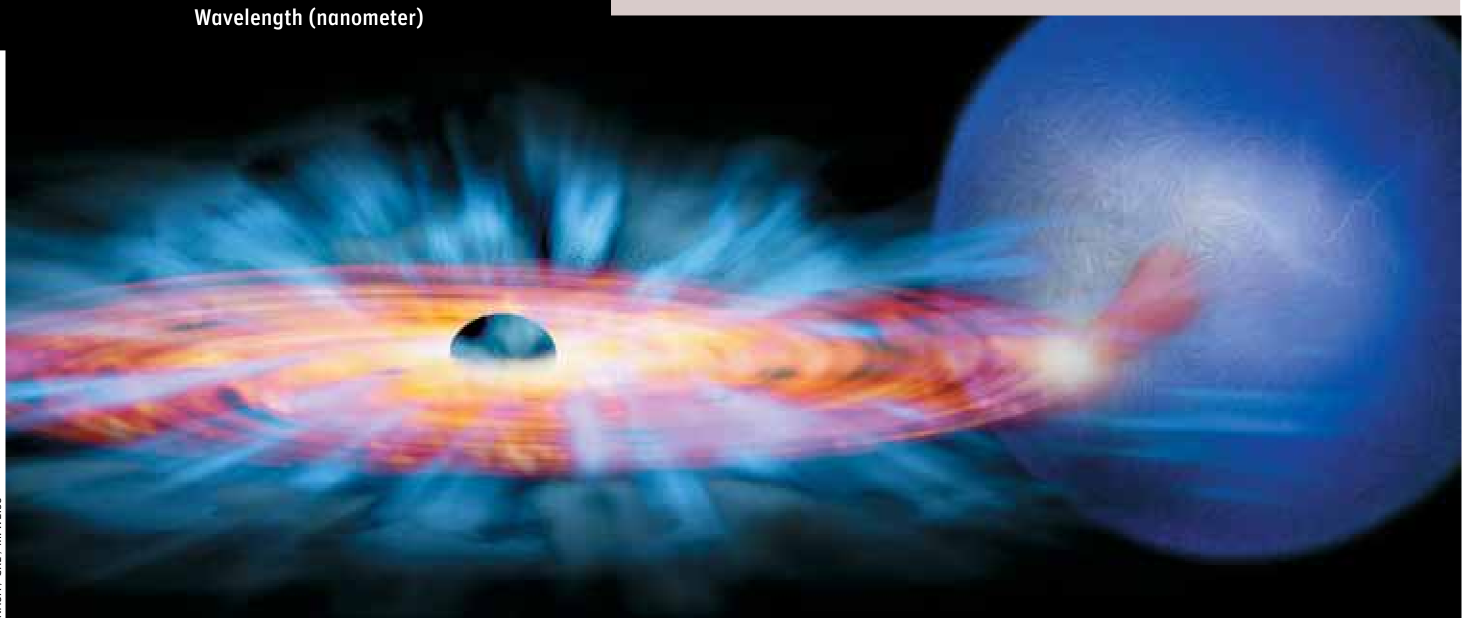
Close to the Edge

Observations of accreting binary-star systems in our galaxy assure scientists they are on the right track. These systems



NASA / CXC / UNIVERSITY OF MICHIGAN / JON MILLER & OTHERS

Left: A Chandra X-ray Observatory spectrum (blue line) of the black hole in the binary system GRO J1655–40 provides strong evidence that magnetic fields drive both accretion and winds. The pronounced dips reveal a potpourri of ionized atoms in the multimillion-degree gas near the black hole. The leftward shift of the blue line relative to a model spectrum (yellow line) shows that the atoms are blueshifted (moving toward Earth) in a high-speed wind. Heat and radiation pressure are too weak to power the observed wind, but magnetic fields have enough energy to do the job. These fields also help drive disk material inward. Below: The GRO J1655–40 binary contains a 7-solar-mass black hole and a companion star.



NASA / CXL / M. WEISS

often contain a white dwarf and a normal star. When their orbit brings the objects close together, gas from the normal star can spill over to the white dwarf, triggering sporadic eruptions. Since these systems are larger and closer to us, in general, than black-hole binaries, their accretion disks are detectable at infrared, visible, and ultraviolet wavelengths. They provide a simple model of accretion for theorists to build upon, although the temperatures are lower and the forces are far less extreme.

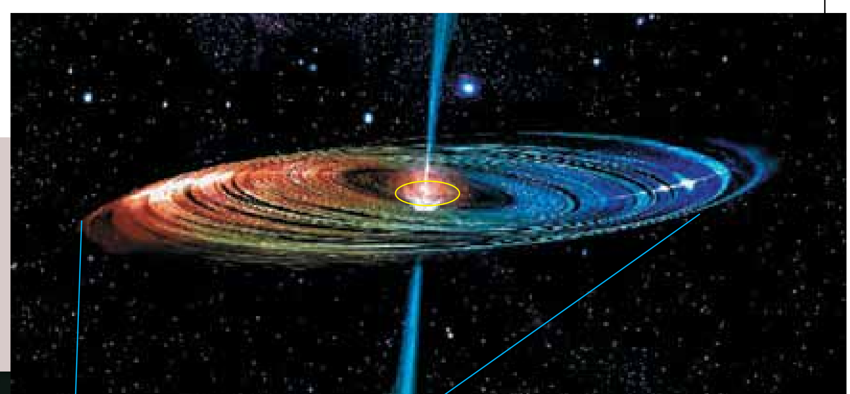
Seeing is believing, and a race is on to image black-hole accretion. Aside from their minuscule angular sizes, accretion disks are enshrouded by dust, gas, and stars, making direct observations extremely challenging. Some disks, however, contain water vapor that produces laser-like beams of microwave energy called masers. The Very Long Baseline Array (VLBA), a string of 10 radio telescopes across North America, has mapped many such masers. The VLBA offers better than 0.001-arcsecond resolution, about 100 times sharper than the Hubble Space Telescope.

A group led by Lincoln Greenhill (Harvard-Smithsonian Center for Astrophysics) has followed the spiral galaxy M106 (NGC 4258) in Ursa Major for 10 years and has identified positions of water vapor in a likely black-hole accretion disk. Observations suggest a thin, warped, and possibly clumpy disk 1.5 light-years across. In 2003 Greenhill's student, Paul Kondratko (Harvard University), used the VLBA to image the cool outer edge of a black-hole accretion disk about 5 light-years across in the nearly edge-on spiral galaxy NGC 3079, also in Ursa Major. This observation provides the strongest evidence of clumps in an accretion disk. Such structures could go on to produce stars and might provide support for MRI turbulence.

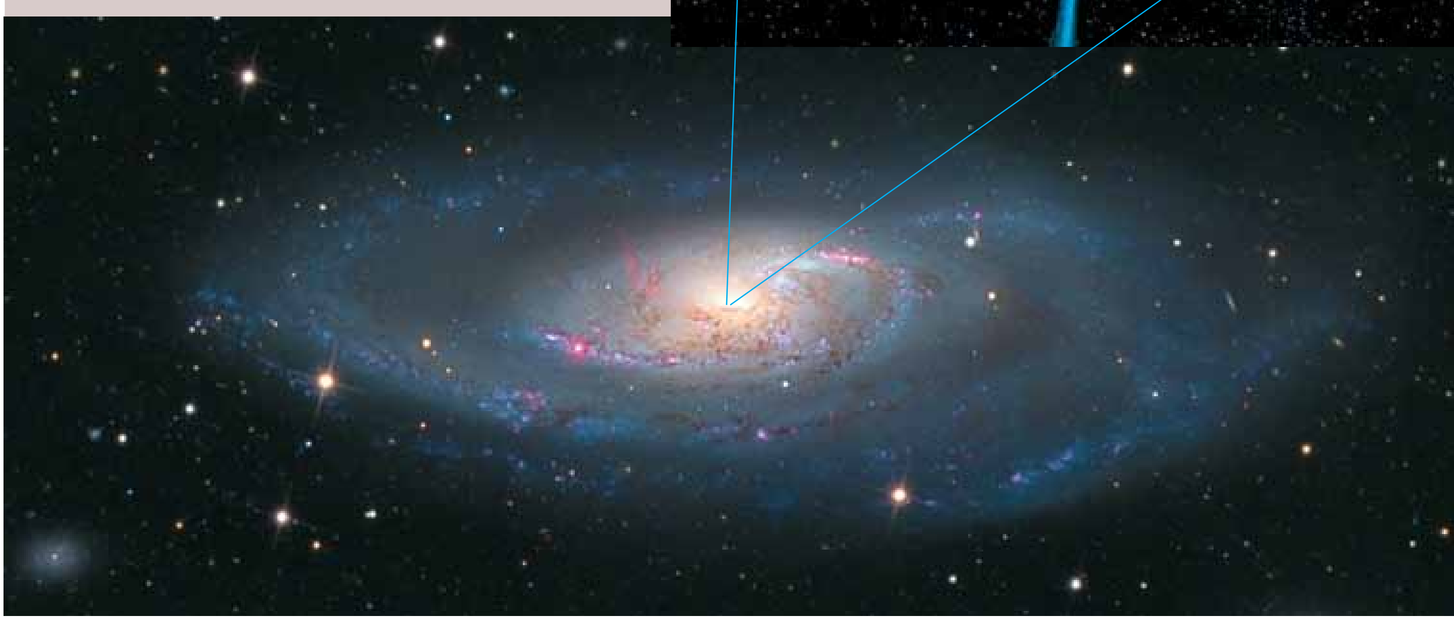
Suzaku, a Japanese X-ray observatory launched in 2005, has a broad-range X-ray detector that is providing new details of hot iron gas whipping around black holes. Scientists using Suzaku announced in October that they have made a series of observations to discern the inclination of an accretion disk relative to Earth's viewing angle, the speed of gas contained within it (more than 10% that of light), and other dynamic finds, such as warped space-time in the inner accretion disk.

NASA's Gamma-ray Large Area Space Telecope (GLAST), scheduled to launch in late 2007, will investigate the connection between accretion disks and jets. Beyond that lies uncertainty. The proposed Constellation-X mission would have the spectral resolution to create movies of gas rotating in the inner regions of an accretion disk. This would at last provide a direct view of the launching pad for forces that have shaped the universe. But NASA's budget calls for a near elimination of high-energy astronomy until at best the end of the next decade (*S&T:* June 2006, page 16), sending the field into a black hole, or at least bringing research time to a standstill. ✴

Christopher Wanjek *of SP Systems is a contract writer for NASA and a freelance health writer. His most recent book,* Food at Work, *is about the obesity epidemic, a different form of accretion. He also writes jokes for Jay Leno's monologue on* The Tonight Show.



LINCOLN GREENHILL & OTHERS



RUSSELL CROMAN

Extremely-high-resolution radio observations of the center of the spiral galaxy M106 (NGC 4258) in Canes Venatici have resolved a thin, warped accretion disk that surrounds a 40-million-solar-mass black hole. The unprecedented detailed observations enabled astronomers to create the computer model of the disk at right.

Spinning Hearts of Darkness

Astronomers are measuring the rotation rates of black holes to determine their formation and history.

DISNEY MUST HAVE had close ties with some of our local TV stations in the 1980s, because it seemed like *The Black Hole* was playing whenever I was home sick from elementary school. My love for this movie blossomed in spite of its cartoonishly stereotypical characters, cheesy costumes, and laughable special effects. I didn't care about the movie except for the black hole itself. The cosmic beast was hypnotic and omnipresent — a dark, gaping maw surrounded by an infalling funnel of fluorescent gas. I was mesmerized. The thought of such an extreme object existing out there was amazing, but even more so was the notion that humans could travel into one and emerge in some other dimension.

I was later disappointed to learn that physicists deem it virtually impossible to journey into a black hole and exit elsewhere intact. In fact, black holes are nature's simplest objects, described only by their mass and spin. So why do so many scientists study these objects, and why does the public gobble up fictional accounts of them? Perhaps it's because black holes represent the ultimate unknown.

Spinning Black Holes

Black holes were given their name because their gravity is so strong that not even light can escape once it passes a critical outer boundary known as the *event horizon*. If we sent a probe past the event horizon with instructions to beam back pictures, the beam would lack the necessary velocity to escape the hole's gravitational pull, even though it would travel at the speed of light. So black holes neither emit light nor let incoming light out once it crosses the event horizon. But we can observe the radiation from infalling gas that doesn't quite make it past the event horizon. This released energy can influence the black hole's surroundings to great distances.

LAURA BRENNEMAN

A black hole actively gorging itself on nearby gas will belch out prodigious energy. These objects also tend to be the ones that offer us the best glimpse into the nature of the innermost accretion disk, closest to the hole and where most of the action is taking place.

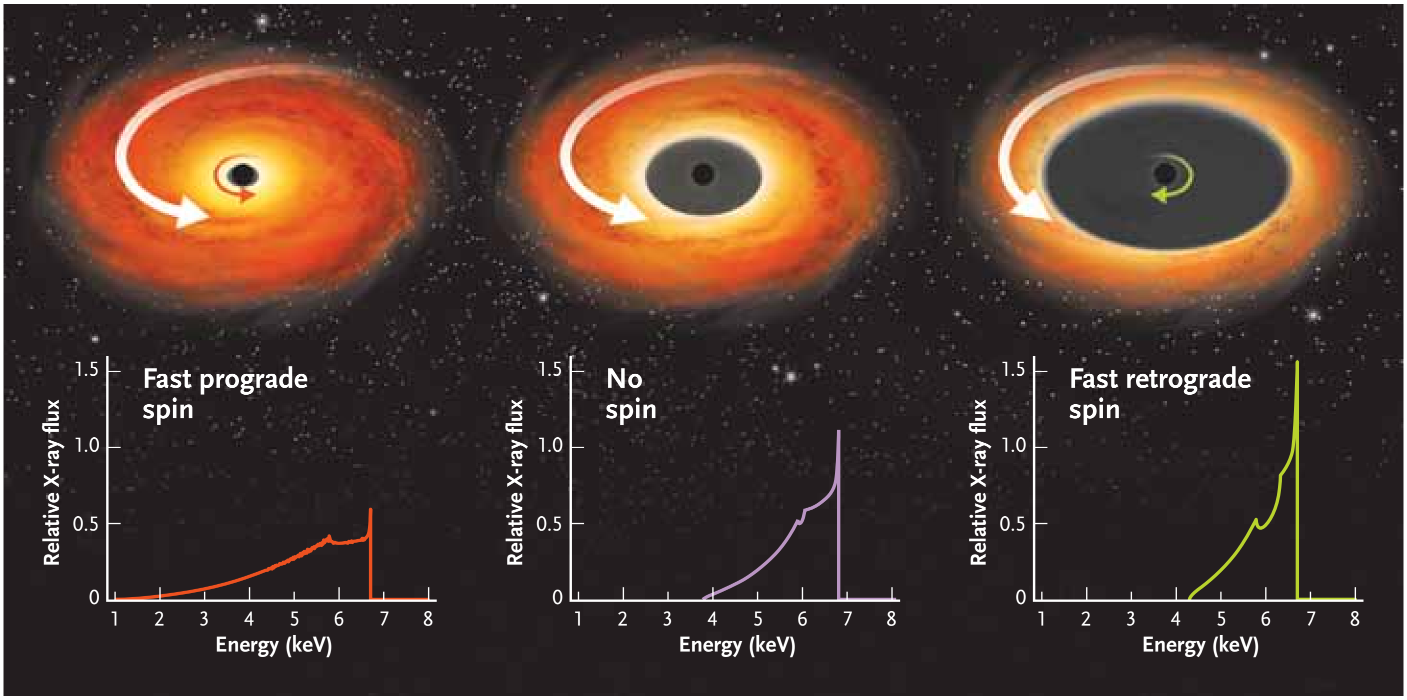
The action that I'm most interested in is how fast the black hole is spinning. We can access this information only by observing radiation coming from very close to the event horizon, where material is so hot that energy is emitted as X rays. Because Earth's atmosphere blocks this

high-energy radiation, orbiting telescopes perform the lion's share of the work.

Why bother figuring out how fast a black hole is spinning? What do we hope to learn that will justify the effort?

First, most galaxies contain supermassive black holes (SMBHs) at their cores, which can range from millions to billions of solar masses. A SMBH plays a pivotal role in shaping its host galaxy. It determines how large its galaxy gets and how many stars it contains, and will do so in spite of having a relative size ratio to its galaxy equivalent to that of a grain of sand in the center of the United States. The black hole accomplishes this feat largely through its unparalleled efficiency in releasing energy from the gas it accretes, and the black hole's spin is a key cog in that engine. Jets released from SMBHs shoot out like geysers from a galaxy's core, keeping intragalactic gas warm enough to stop star formation in the host galaxy,

GAPING MAW Like almost all objects in space, black holes rotate. Along with mass, the spin rate is one of only two fundamental characteristics of a black hole, and it has a profound influence on the surrounding spacetime and how the black hole accretes matter. This artistic rendering shows a black hole accreting material from its surrounding disk.



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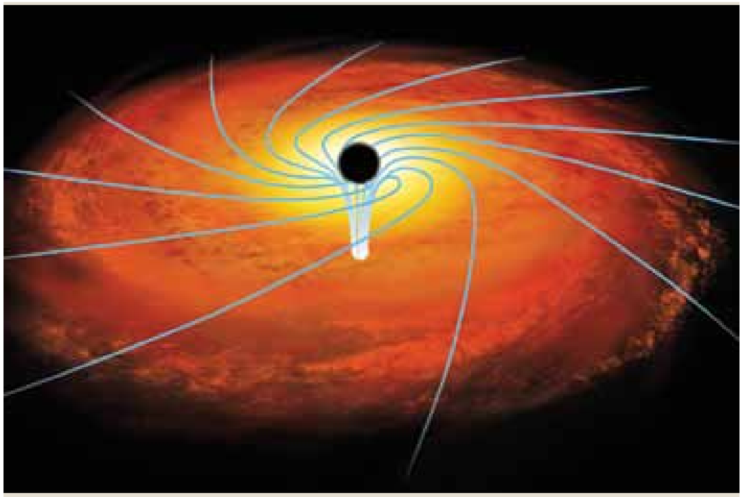

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SPIN *Above:* A black hole's spin plays a pivotal role in determining how close material can orbit before falling into the abyss. Material orbits farther from a nonspinning black hole, and farther still from a retrograde hole. Simulated spectra of the Fe Kα line are below. *Left:* The faster a black hole spins, the larger the frame dragging (represented by blue lines). This effect of general relativity allows material to orbit very close to a fast-spinning, prograde black hole.

THE POINT OF NO RETURN

All black holes have an innermost stable circular orbit (ISCO), the distance from the event horizon at which the energy and angular momentum of orbiting material is no longer sufficient to counteract the inward pull of gravity. Once material crosses the ISCO, it plunges into the black hole on a ballistic trajectory.

The ISCO's distance from the event horizon depends on the black hole's mass and spin. According to general relativity, a spinning massive object drags the surrounding spacetime, an effect known as frame dragging. A fast-spinning black hole will spin up nearby spacetime, imparting more angular momentum to material orbiting in the inner accretion disk. This energy enables the material to resist the black hole's gravity, keeping it from plunging into the hole at the distance it otherwise would have without the help of frame dragging.

thus regulating its size. Physicists think jet power is directly related to black hole spin.

Second, measuring black hole spin can tell us about the recent growth history of a SMBH and its host galaxy. According to computer simulations by Marta Volonteri (University of Michigan) and her collaborators, black holes that grow primarily by accretion will spin faster than those that grow mostly by mergers with other black holes. Prolonged accretion usually funnels gas onto the accretion disk in the same direction that it (and the black hole) is already spinning, increasing the hole's spin. In contrast, black hole mergers occur at random angles, which can alter the spin direction and speed of the resulting black hole. SMBH mergers occur millions of years after their host galaxies merge (*S&T:* April 2009, page 26).

Spin, therefore, is an excellent diagnostic for assessing a black hole's recent history of mergers versus accretion. As the number of SMBHs with reliable black hole spin measurements grows, so too will our knowledge of spin demographics and its relation to other physical properties of SMBH systems such as mass, accretion rate, jet power, and host-galaxy mass and type.

In the case of black holes that originate from dying massive stars (the so-called galactic black holes, or GBHs), constraining their spin rates will provide insight into the nature of supernovae, which are the most common precursors of GBH formation. GBH spins are not likely to undergo significant evolution, since a black hole must accrete roughly its own mass in order to have its spin change appreciably, and the typical supply of gas for GBHs is too scarce to provide enough fuel. Therefore, GBH spins are thought to be natal — the result of the collapse of spinning stellar cores.

Measuring Spin

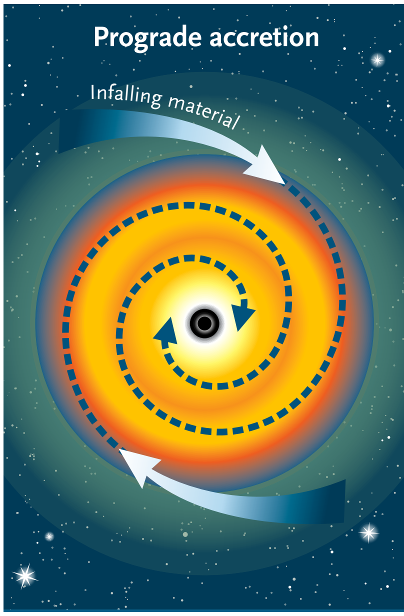
The black hole's spin determines the distance of the accretion disk's inner edge from the event horizon. According to Einstein's general theory of relativity, if the black hole and its accretion disk spin in the same direction (prograde), the faster the black hole spins, the closer the disk's inner edge will be to the event horizon. If the hole and disk spin in opposite directions (retrograde), then the opposite is true; in fact, a maximally spinning retrograde black hole will have a disk inner edge 9 times farther away than the event horizon. If the black hole is not spinning at all, the disk's inner edge is located 3 times farther away from the event horizon. So if we can determine the edge of the innermost disk, we can infer the black hole's spin.

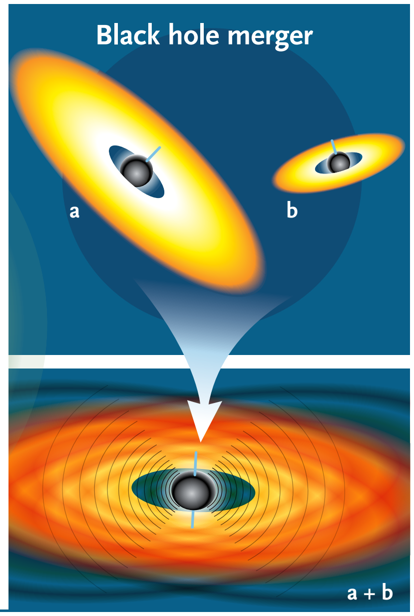
Unfortunately, most SMBHs are so far away that their inner disks are too small to be seen in an image. Currently, the most reliable way to constrain an accretion disk's innermost edge involves examining the spectrum of X rays we observe from the inner disk. There are two techniques employed to constrain the inner edge from X-ray spectra: spectral-line modeling and thermal modeling.

Spectral-line modeling typically requires the detection of an iron emission line known as Fe Kα. This strong spectral feature is often emitted from gas throughout the accretion disk, but when it's observed from the inner disk, the gas's rapid motion drastically alters the line's shape. Gas in the inner disk is closer to the event horizon, and if we imagine a black hole's strong gravity acting on the fabric of the surrounding spacetime like a bowling ball in the middle of a trampoline, this gas is deeper in the valley, so to speak. As such, it orbits the black hole extremely rapidly and is also subject to the peculiarities of warped spacetime near a black hole as dictated by relativity.

The Fe Kα line's shape is thus quite broadened and skewed. The degree of broadening and distortion is directly related to the location of the disk's inner edge, making these broad Fe Kα lines ideal probes of black hole spin. By applying spectral models that take relativity into account, we can use these broad emission spectral lines to constrain a black hole's spin.

Thermal modeling cannot be used for SMBHs; it's useful only in GBH systems where the accretion disk is so hot that it radiates thermally in X rays, and in which the





S&T: LEAH TISCIONE

TORQUING A BLACK HOLE
Above left: A black hole will "spin up" if it accretes matter from a disk revolving in the same direction. If it can accrete enough material, it can spin up almost to the maximum possible velocity allowed by relativity — the speed of light. *Above right:* When two black holes collide, they can do so at random angles. Depending on the collision angle, the merger can either spin up or spin down the resulting black hole, and it can torque its rotational axis.

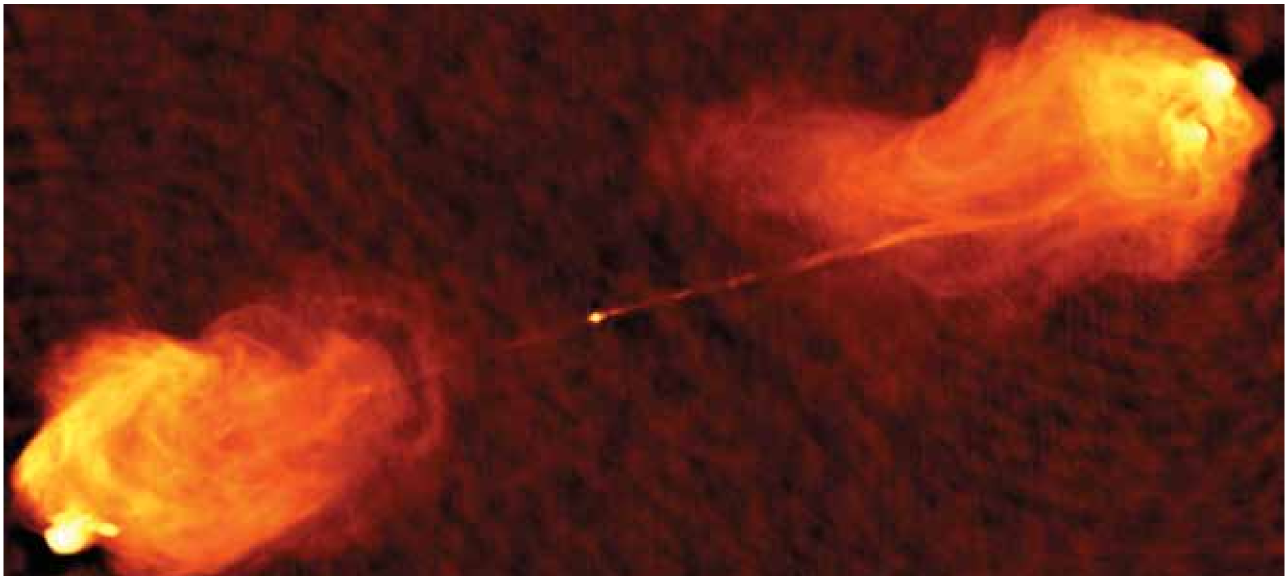
Galactic Black Holes

Black Hole	Spin (a)	Method
GRS 1915+105	0.98±0.01	SM
	0.99±0.01	TM
LMC X-1	0.92±0.06	TM
M33 X-7	0.84±0.05	TM
4U 1543–47	0.30±0.10	SM
	0.80±0.05	TM
J1655–40	0.98±0.01	SM
	0.70±0.05	TM
A0620–00	0.12±0.19	TM
J1550–564	0.76±0.01	SM
	0.78±0.02	TM
J1650–500	0.79±0.01	SM
	0.87±0.01	TM
GX 339–4	0.94±0.02	SM
J1711.6–3808	0.60±0.30	SM
	0.60±0.40	TM
J1908+094	0.75±0.09	SM
	0.75±0.09	TM
Cygnus X-1	0.05±0.01	SM
	<0.05	TM
J1753.5–0127	0.76±0.15	SM
	0.40±0.45	TM
J1652–453	0.50±0.10	SM

SM = Spectral-line Modeling   TM = Thermal Modeling

Supermassive Black Holes

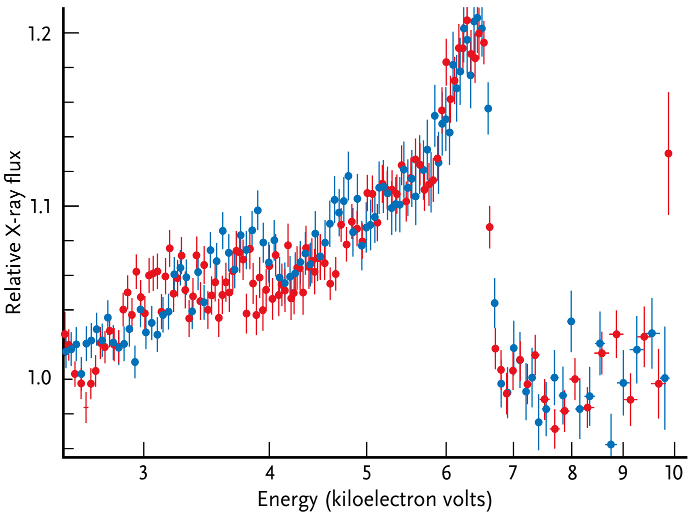
Black Hole	Spin (a)
MCG-6-30-15	>0.98
Fairall 9	0.65±0.05
J2127.4+5654	0.60±0.20
1H0707–495	>0.98
Markarian 79	0.70±0.10
NGC 7469	0.69±0.09
Markarian 335	0.70±0.12
NGC 3783	>0.98



NRAO / AUI / RICHARD PERLEY, ET AL.

POWERFUL JET Like other supermassive black holes at the centers of large galaxies, the beast at the center of galaxy Cygnus A (seen as the bright central dot in this radio image) shoots out jets that stretch for hundreds of thousands of light-years. According to a recent theory, the most powerful jets like this one result from retrograde-spinning black holes.

black hole's distance and mass are very accurately known. The disk's X-ray luminosity is a simple function of its temperature and size (in this case, the size is the radius of the inner disk edge). By measuring the disk's flux and temperature, and if we know the system's distance and mass, we can compute the inner disk's radius and thus infer the black hole's spin. These two methods can be used to check each other on GBH spin measurements.



S&T: G. DINDERMAN, SOURCE: L. BRENNEMAN / A. FABIAN / G. MINIUTTI, ET AL.

BLACK HOLE SPIN SIGNATURE Using XMM-Newton date (blue) and Suzaku data (red), the author's research group analyzed the special iron spectral line (Fe Kα) from the inner part of the accretion disk around the supermassive black hole in the galaxy MCG-6-30-15. The specific distorted shape of the line indicates a black hole spinning very close to the speed of light, the maximum possible rotation velocity.

Demographics of Black Hole Spin

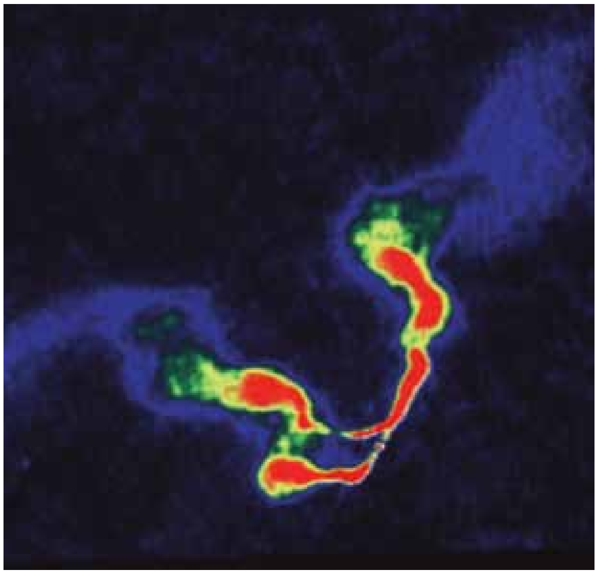
Several teams have obtained black hole spin measurements resulting from X-ray emission spectral-line modeling of broad iron lines (in SMBHs and GBHs), as well as thermal modeling (GBHs only). The data must have excellent signal-to-noise and spectral resolution (requiring advanced CCD detectors or calorimeters). Current X-ray space observatories have provided unprecedented advances in this field, allowing robust constraints on black hole spin in several SMBHs and GBHs.

Black hole spin can range from –1 to 1, where negative values represent retrograde black hole spin, zero means no spin, and positive values imply prograde spin relative to the accretion disk. An absolute value of 1 is the maximum possible prograde or retrograde spin as dictated by general relativity (the velocity at which the event horizon is spinning at the speed of light). While we don't yet have a large enough sample of black hole spins measured for either SMBHs or GBHs to infer any meaningful correlations between spin and other system properties, we can say that the measured spins span a large range of values rather than being clustered around high or low values.

GBHs exhibit a broader range of spins than do SMBHs, though we have fewer SMBHs with statistically robust spin constraints. Three GBH measurements are consistent with near-zero or negative spins, though models allowing retrograde black hole spin have only been developed within the past year by Thomas Dauser (University of Erlangen-Nuremberg, Germany) and his colleagues. By contrast, none of the SMBHs have a spin less than 0.4, taking model-fitting errors into account. In fact, three of the eight measured sources have spins above

0.9, implying that these black holes have experienced a recent period of prolonged prograde accretion, possibly in addition to major mergers over billions of years.

Although the exact role of spin in jet production remains unclear, a recent theoretical study by David Garofalo (JPL/Caltech) and his colleagues concludes that retrograde-spinning black holes can power jets up to 100 times stronger than their prograde counterparts, but that retrograde spin will only persist for a short fraction of a SMBH's lifetime, usually immediately after a major galaxy merger that leads to an SMBH merger. If correct, the most powerful jets originate from retrograde-spinning SMBHs, a conclusion reinforced by the small number of such observed sources, and the fact that most galaxies with luminous jets are ellipticals, as expected after major galaxy mergers. Constraining black hole spin in galaxies with luminous jets will provide evidence to support or refute this theory.



NRAO / AUI / FRAZER OWEN, ET AL.

SPIN FLIP This image of radio galaxy 3C 75 shows four jets aimed in different directions. This could be the signature of a black hole binary. When the black holes coalesce, the resulting hole may briefly have a spin direction opposite of its accretion disk.

Future Directions

What is the distribution of black hole spins among SMBHs and GBHs? How does spin correlate with other environmental variables such as accretion rate, host galaxy shape, and black hole mass? What role does spin play in the triggering of powerful jets from black hole systems, and how does this feedback dictate the host galaxy's evolution? These are just a few important questions remaining to be answered in black hole astrophysics.

A larger sample size of SMBH and GBH spins is needed to begin finding answers. Such a census of black hole spin is currently underway using spectra from the Suzaku, Chandra, and XMM-Newton X-ray observatories.

I'm one of the lead investigators behind the effort to measure SMBH spin using broad iron spectral lines. Our collaboration hopes to utilize long Suzaku observations of the SMBHs in six active galaxies in order to increase our total number of robust SMBH spin measurements. Because of the sensitivity of our spin measurements, we must combine several days worth of observations in order to achieve the necessary data quality.

Ideally, we'd like to precisely measure the broad iron line profile during a single orbit of inner-accretion-disk material, rather than having to rely on long exposures spanning many orbits to achieve the required signal-to-noise, as we do currently. While the hole's spin is expected to remain constant over long timescales, the broad iron line's shape can change dramatically if the nature of the accretion flow is changing. Measuring these changes will allow us to compare how black hole spin and dynamical processes in the accretion disk shape the inner accretion flow.

The next generation of X-ray observatories will make such observations of SMBHs and GBHs a reality. Japan's Astro-H mission (scheduled for launch in 2014) will improve on Suzaku's capabilities by roughly a factor of 20. NASA's Gravity and Extreme Magnetism Small explorer (GEMS, also scheduled for launch in 2014) will bring the science of polarimetry to bear on measuring black hole spin, allowing constraints to be placed on spin independent of spectral modeling. The International X-ray Observatory (IXO), if built, would improve on the collecting area of current X-ray missions by a factor of 100 while simultaneously improving on the spectral resolution of Astro-H by a factor of 3. Combined, these sensitivity increases would make IXO an unparalleled tool with which to measure black hole spin, enabling hundreds of fainter SMBHs and GBHs to be observed. We could finally probe the demographics of black hole spin in a larger statistical sense.

We currently live in the golden age of X-ray astronomy, with several powerful observatories in orbit. Because X rays from galaxy cores often originate from material very close to a SMBH's event horizon and encode information about the black hole's spin, we are now finally poised to probe this fascinating, fundamental property of black holes. In so doing, we can unlock the mysteries of how these cosmic vortexes consume and emit energy, shape the lives of galaxies, and influence their surroundings on scales that dwarf them by many orders of magnitude.

Surely, Disney would find this a worthy adventure. ✦

__Laura Brenneman__, a postdoctoral fellow at the Harvard-Smithsonian Center for Astrophysics, has authored numerous papers on the topic of black hole spin. She also played baseball for the U.S. Women's National Team from 2002–07.

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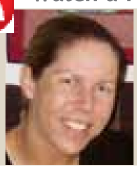
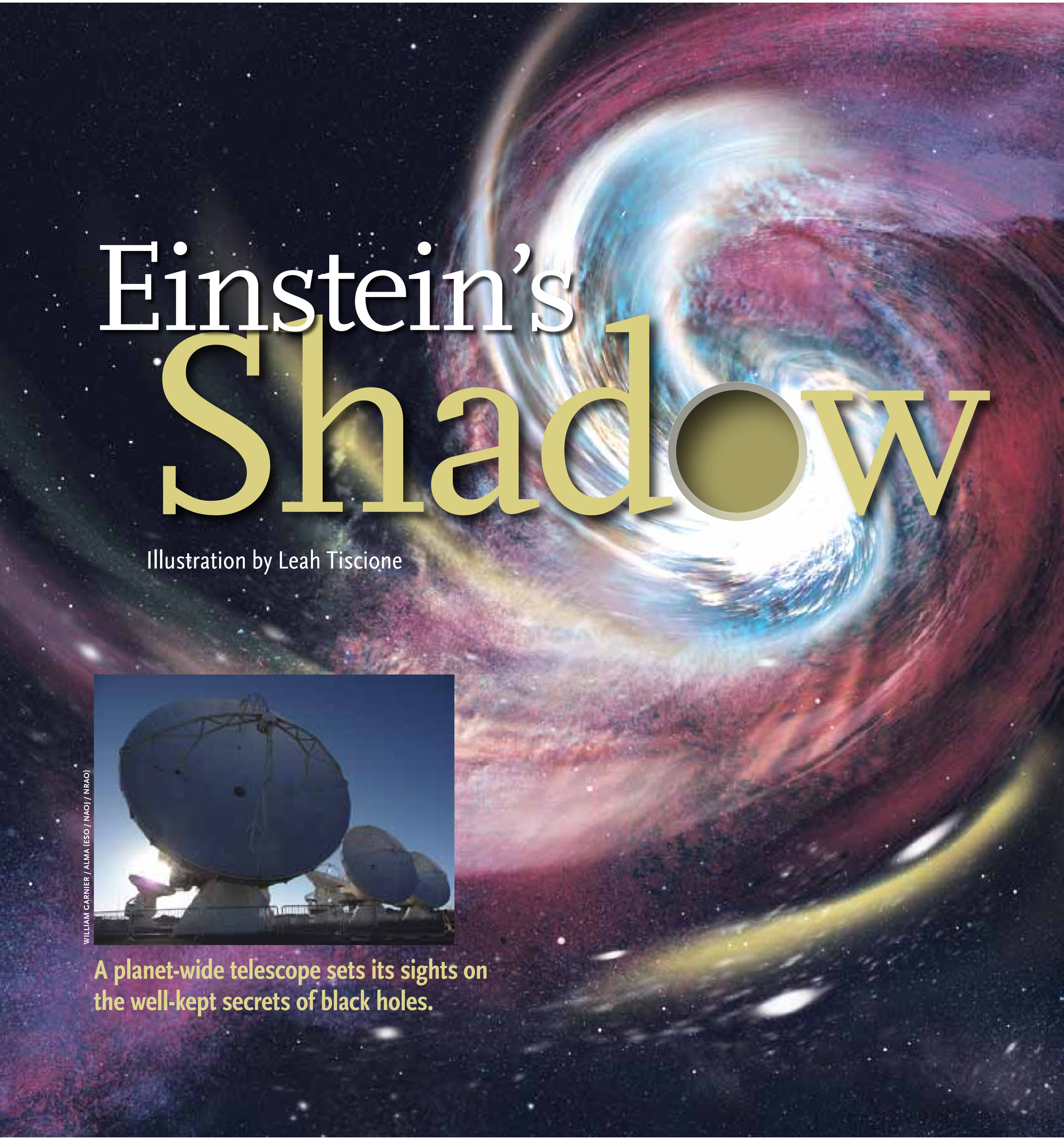


To watch a video conversation with author Laura Brenneman, visit SkyandTelescope.com/bhspin.



Einstein's Shadow

Illustration by Leah Tiscione

WILLIAM GARNIER / ALMA (ESO / NAOJ / NRAO)

A planet-wide telescope sets its sights on the well-kept secrets of black holes.

Camille M. Carlisle

These days, black holes are about as common as dust bunnies.

Millions of them dot the Milky Way's disk in stellar binary systems, gorging on material from their companion stars. Supermassive beasts lurk in the cores of most large galaxies and may even influence their hosts' formation and evolution.

But even though black holes appear to be just about everywhere, we've never actually seen one. That might seem a moot point, considering they swallow light. Nevertheless, as excellent as the circumstantial evidence is for their existence, black holes may not look how we think they do. Nor does current evidence prove the veracity of general relativity (GR), Einstein's theory of gravity that predicts — much to its creator's horror — the formation of these compact massive objects. We don't even know for certain that relativity's description of spacetime, and black holes, is correct: GR has never been tested in strong gravitational fields like those created by gargantuan black holes.

All that may be about to change. Astronomers across the world are joining forces to create the Event Horizon Telescope (EHT), a network of radio observatories that will stretch from the South Pole to Hawaii and southern Europe. These antennas will work together like a single planet-sized dish, peering into galactic hearts to study what happens near the event horizon, the closest distance light can approach before a black hole's gravity drags it so deep inside that we can no longer see it falling in. The EHT should unmask black holes, revealing how they feed and grow. More important, it will put everything we know — or think we know — about gravity to the test.

The Silhouette

So far GR has passed every test, from explaining delays in satellite signals to predicting the orbits of neutron stars (*S&T:* August 2010, page 28). But Newtonian mechanics also passed many tests in the two centuries between its publication and Einstein's theory of gravity. And physicists are well aware that GR fails to describe the microscopic realm, where they have to turn to quantum mechanics. The question is, how far can GR be pushed?

To answer this question, astronomers must probe where Newtonian mechanics breaks down: the innermost stable circular orbit, or ISCO (*S&T:* May 2011, page 20). The ISCO is the closest path material can follow around a black hole without falling in. But even though material inside the ISCO may still lie outside the event horizon, that material will eventually plunge into the black hole, no matter how fast it's going.

"Newton would look at that orbit and say 'That's crazy,'" says EHT project leader Sheperd Doeleman (MIT Haystack Observatory). There's no ISCO in Newtonian gravity: as long as material stays outside the object it's circling, it will continue to orbit, without spiraling in. But in GR, a black hole's gravitational potential is proportional to $1/r^3$ (r is the distance between the black hole and an orbiting particle) instead of the $1/r$ of Newtonian theory — which means the well sinks a whole lot more near the black hole in GR than Newtonian theory predicts. This effect overwhelms even the centrifugal energy of orbital motion. Circular paths become unstable, and like a penny in a coin vortex, material plunges past the event horizon.

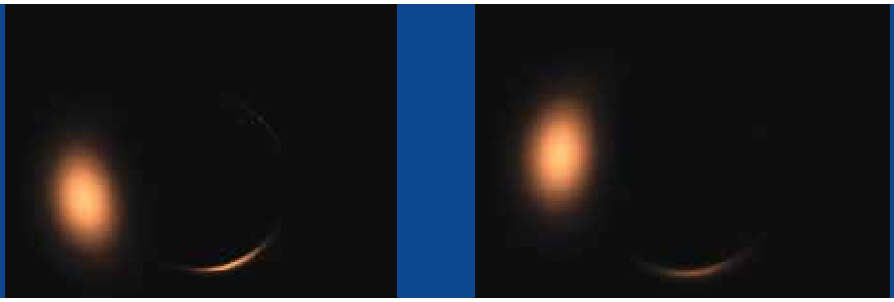
CAPTURING THE BEAST Famously camera-shy, black holes may finally reveal themselves to astronomers' careful gaze in the next decade. This simulated image shows what our Milky Way's central black hole might look like to the Event Horizon Telescope, with the silhouette created by the extreme bending of light from accreting matter around the object.

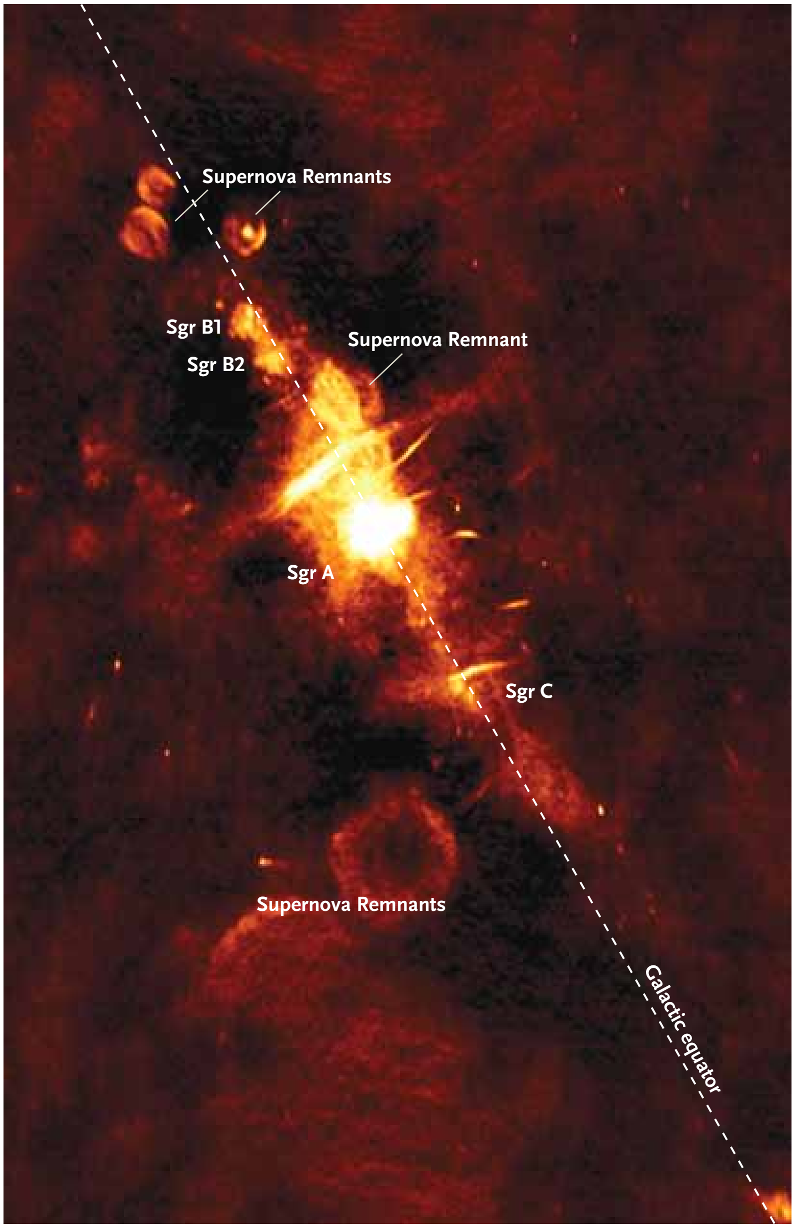
AVERY BRODERICK (UNIV. OF WATERLOO & PERIMETER INST.) / ABRAHAM LOEB (HARVARD-SMITHSONIAN CFA)

WHAT IS A BLACK HOLE?

A black hole is an object that is so massive and compact that it creates an inescapable, four-dimensional pit in spacetime. *But* a black hole is not made of matter: it doesn't have a hard surface. From the inside, a black hole is a cosmic whirlpool, an object made of warped spacetime, whose outer "edge" is the event horizon. From the outside, though, a black hole can be completely described with just three numbers: its spin, mass, and electric charge. Generally there's no overall charge, so charge can be ignored, reducing the variables to two.

VIEWING ANGLES Depending on how the accretion disk around our galaxy's central black hole is tilted to our line of sight, light from an orbiting hot spot could be lensed in a variety of ways. This sequence moves from looking down at the disk from above to seeing it from its side, with the spot behind the hole. The strength of the black hole's gravity determines how light bends near the event horizon.





NAMIR KASSIM (NAVAL RESEARCH LABORATORY) ET AL.

A SINGULAR NEIGHBORHOOD Although gas and dust obscure the Milky Way's center in visible light, its innermost parts show clearly in this radio image made using data from the NRAO's Very Large Array. The diagonal orientation results from the Milky Way's disk (Earth's orbit around the Sun is inclined to the galactic plane). Inside the Sgr A region hides the black hole known as Sgr A*.

GR simulations make specific predictions about how the near-ISCO environment should appear to EHT scopes. If a disk of gas and dust surrounds a black hole, the event horizon should look like a dark silhouette, surrounded by the glow of accreting material and framed with streaks of light. The silhouette effect happens for two reasons. First, light is fighting to survive. The black hole sits in the midst of glowing accreting material heated by friction and gravitational acceleration. But toward the disk's center, light has to struggle to escape the indentation the black hole makes in the fabric of spacetime. As a photon loses energy, its wavelength becomes longer, until it's stretched to infinity and right out of existence.

The second and prevailing reason for the silhouette effect is what happens to radiation emitted by material on the event horizon's far side. The black hole blocks this light from our direct view, but it gravitationally lenses this radiation to curve around the central object to where we can see it, creating a darker center. The lensed light should form long streaks around the silhouette, looking rather like the diamond ring of a total solar eclipse — except in this image the light is emitted at radio wavelengths, not optical. While this radiation is gravitationally redshifted by the time it reaches us, the effect is insubstantial: a photon originating from the ISCO with a wavelength of 1.06 mm arrives at Earth at 1.3 mm.

These processes create what looks like a shadow but isn't. And how streaks stretch around the silhouette depends on how the black hole's gravity lenses light near the ISCO — which depends on what kind of gravity astronomers are dealing with. If observations reveal unforeseen phenomena (such as bizarre silhouette shapes), it could indicate that Einstein's theory breaks down in strong gravity.

Images also depend on how matter accretes onto black holes. Material falling in radially (that is, without orbiting) onto a nonspinning black hole would create a symmetrical image with a central "shadow." But if the accreting material is orbiting the black hole, the image will appear asymmetrical because material moving toward us looks brighter due to relativistic effects.

That's all in theory. While theorists have constructed excellent models over the past three decades of what goes on around black holes, they need observations to confirm

A. BRODERICK (UNIV. OF WATERLOO & PERIMETER INST.) / A. LOEB (HARVARD-SMITHSONIAN CFA)

them. As Abraham Loeb (Harvard-Smithsonian Center for Astrophysics) explains, "It would be very instructive to see, for the first time, how nature does it in reality."

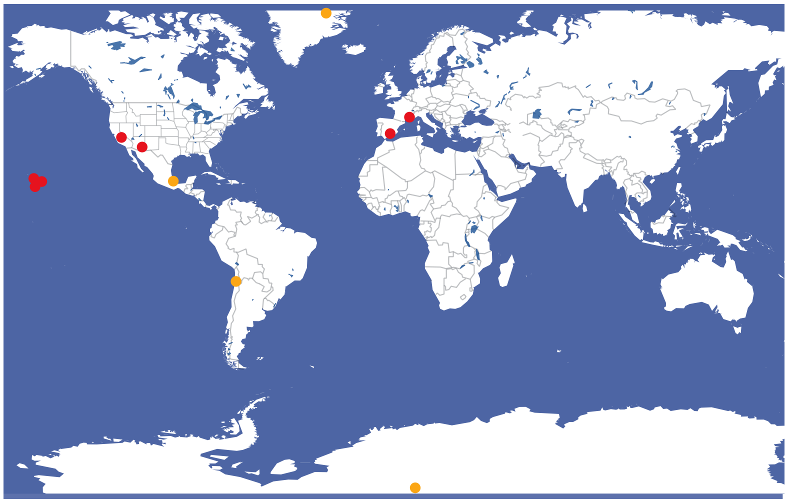
Acquiring Target

The EHT's first target is Sagittarius A* (abbreviated Sgr A* and pronounced "A-star"), the supermassive black hole candidate at the center of our Milky Way. Measurements by UCLA and Max Planck Institute astronomers have pegged our galaxy's beast at roughly 4 million solar masses by measuring the orbital motions of stars in the galactic center. At 26,000 light-years' distance, Sgr A*'s event horizon will appear 53 microarcseconds wide. That's about the size of a poppy seed in Los Angeles seen from New York City. Even so, Sgr A* has the largest apparent event horizon of any black hole candidate.

Astronomers plan to zoom in on this minuscule target with a technique called Very Long Baseline Interferometry. VLBI combines observations from radio telescopes far away from one another into a single enhanced image, just as though astronomers had used one big dish that spanned the distance between the scopes. Because a telescope's theoretical resolution improves as its diameter increases, VLBI dramatically improves observing capabilities. The diameter of a "virtual" radio telescope stretching from Hawaii to Chile, for example, has the same resolution as that of a single dish 9,450 kilometers (about 5,870 miles) wide. Astronomers at different locations must observe simultaneously, but they can combine their observations to create a single, cohesive picture.

In 2007 EHT astronomers led by Doeleman observed Sgr A* using a three-station VLBI array that combined the Arizona Radio Observatory's 10-meter Submillimeter Telescope (ARO/SMT), a 10-meter element of the Combined Array for Research in Millimeter-wave Astronomy (CARMA) in California, and the 15-meter James Clerk Maxwell Telescope (JCMT) atop Mauna Kea. Observing in the 1.3-mm (230-GHz) band, the astronomers detected structure in the ionized gas right around Sgr A* at a distance of roughly four times the size of the event horizon (*S&T:* March 2010, page 14).

But astronomers don't yet know what that structure is. "You can't reconstruct the image from only three telescopes," says Doeleman. "So I know there's something compact there, I know there's something about the size of the event horizon, but I can't tell you exactly what it looks like. To do that, we have to extend the VLBI to more telescopes."



S&T: GREGG DINDERMAN

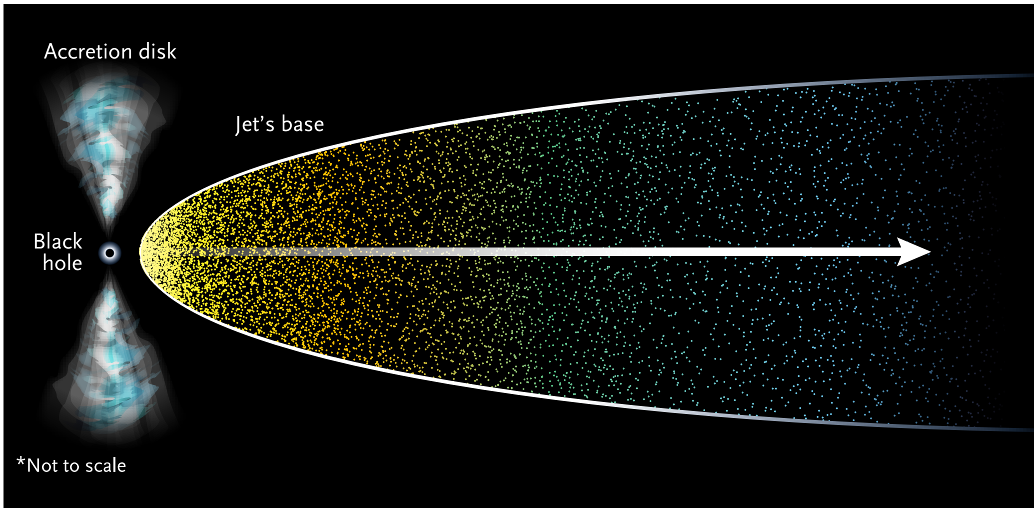
ALL OVER THE MAP Capturing a black hole takes a planet-sized telescope — or a planet covered in telescopes working together. Shown are the various international sites participating, or expected to participate, in Event Horizon Telescope observations.

The observations constrained Sgr A*'s angular size to 37 microarcseconds, which translates to a physical diameter of about four-tenths of an astronomical unit (a.u.). You'll notice that that number is smaller than the event horizon's size: Doeleman and his colleagues think the Sgr A* source may be a bright spot in an accretion disk or a jet that is slightly offset from the unseen black hole.

In April 2009 the astronomers added a second CARMA scope and spotted a flare in Sgr A* that appeared between the second and third observing days. This variability matches similar activity seen in other multiwavelength campaigns, bolstering the claim of event-horizon-scale structure. VLBI measurements also show that the Milky Way's central black hole probably doesn't spin very fast and that its accretion disk is more edge-on than face-on from our vantage point.

Violence Unmasked: M87

EHT astronomers also want to tackle the center of M87. This giant elliptical galaxy lies roughly 52 million light-



S&T: LEAH TISCIONE

THE HEART OF THE MATTER STREAM Deep inside the elliptical galaxy M87, a supermassive black hole creates a high-speed jet that shoots from the galaxy's center. Recent observations suggest the jet indeed begins at a fixed point; everything shown here hides in the jet's bright core (shown below).

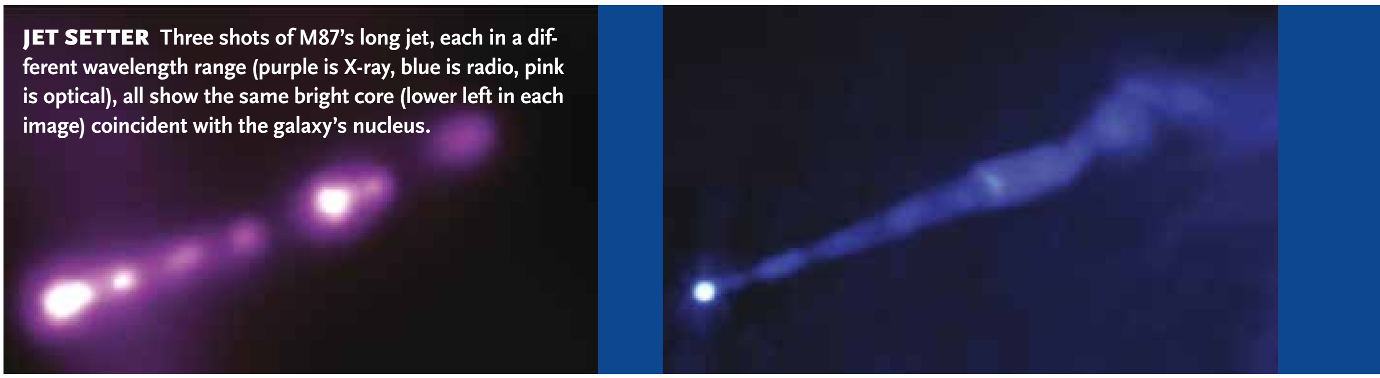
years away, 2,000 times farther than Sgr A*. Astronomers think that a 6.4-billion-solar-mass black hole (more than 1,000 times more massive than Sgr A*) lurks in M87's core. A black hole of that extreme mass would have an event horizon roughly 135 a.u. wide, just larger than the Kuiper Belt. But at M87's distance, the event horizon's angular size would be less than 8 microarcseconds — amazingly small, and yet this tiny horizon is the second largest candidate after the Milky Way's black hole. Lensing effects may make the accretion disk's inner edge appear larger, too, between 34 and 54 microarcseconds.

M87 is also fascinating because its core emits incredible amounts of radiation. Such active galaxies can produce 1 trillion times the Sun's energy, all in a region smaller than our solar system. Many active galactic nuclei shoot jets of plasma into intergalactic space (*S&T:* April 2010, page 20); M87's single visible jet stretches 5,000 light-years long.

Last September Japanese scientists not involved with the EHT reported VLBI measurements suggesting that M87's jet begins at a fixed point 14 to 23 times the event horizon's diameter from the black hole. That distance is surprisingly small: previous studies of jets that point straight at Earth had suggested separations thousands of times larger. But M87's jet is somewhat sideways from Earth's point of view, so the Japanese astronomers could see how the stream's bright, unresolved base changes location with wavelength, appearing to narrow in on the black hole's location. The team observed at six wavelengths from 2 to 43 GHz using an array of 10 antennas stretching from Hawaii to the Virgin Islands. With that span they could resolve details 400 times finer than Hubble can in optical light. Resolution at EHT wavelengths should be several times better and should allow radio astronomers to directly image both the jet's origin and accretion flow around the black hole.

M87 is a particularly attractive target because its light output varies on a much longer timescale than Sgr A*. Why these sources vary isn't definitively known. Fluctuations may be caused by "hot spots" in the accretion disk, which appear to flare as they approach us.

These structural changes during observing runs will smear images, reducing resolution and making it more difficult to image a black hole's silhouette. But high-frequency VLBI should be able to resolve changing structure from orbiting hot spots by capturing snapshots over short time intervals. Source signals can then be summed to reflect how the structure changes with time. Watching these changes will allow EHT astronomers to time hot-



JET SETTER Three shots of M87's long jet, each in a different wavelength range (purple is X-ray, blue is radio, pink is optical), all show the same bright core (lower left in each image) coincident with the galaxy's nucleus.

X-RAY: NASA / CXC / MIT / H. MARSHALL ET AL.; RADIO: F. ZHOU, F. OWEN (NRAO), J. BIRETTA (STSCI); OPTICAL: NASA / STSCI / UMBC / E. PERLMAN ET AL.

WILLIAM GARNIER / ALMA (ESO / NAOJ / NRAO)

MANY EYES MAKE LIGHT WORK **The Atacama Large Millimeter/submillimeter Array (ALMA) is taking shape in the northern Chilean desert. Only a fraction of the planned 66 antennas appear in this photo.**

spot orbits, and because hot spots are close to the black hole, their orbits move through relativistic anomalies not described by Newtonian gravity. By clocking these orbits, observers can test predictions of spacetime's structure near the ISCO.

"I honestly think that the real gold mine will be the non-imaging observations in which we monitor the time variability of Sgr A*," says Doeleman. By timing "blob" orbits near the ISCO, the team can also estimate the black hole's spin by comparing the measured orbital period with the predicted one to see if the monster's spin is speeding up disk rotation. It is these orbits, even more than the silhouette, that will determine how closely Einstein's predictions match reality.

What's Next

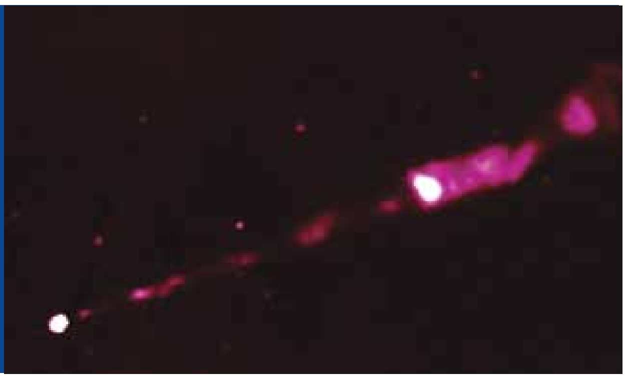
The EHT project has made great strides in the last few years, but there's still a long road ahead. With more than a dozen contributing institutes in Asia, North America, and Europe, the astronomers have many details to iron out.

One detail is the installation of masers — devices that use stimulated microwave emission from atoms to keep time. Because the EHT will combine observations conducted simultaneously around the world, accurate clocks are essential: the masers lose only a second over 100 million years. But some facilities' masers need maintenance, and others don't even have one yet.

Telescope modifications and various measurements also have to be made. To properly reconstruct the observations back at Haystack Observatory — Doeleman's home base and EHT headquarters — astronomers need to know each observing site's location to within a couple of feet. Such exactitude can take hours to calibrate, and earthquakes and spreading tectonic plates change site locations over time.

Achieving finer resolution will be the key to success. EHT astronomers plan to improve resolution in part by moving to shorter wavelengths. They're particularly focused on the 0.8-mm (345-GHz) band which, along with 1.3 mm (which Doeleman's team used in 2007 and 2009), is one of two main atmospheric windows in the millimeter/submillimeter range.

The challenge with 345 GHz is weather. Atmospheric



THE EVENT HORIZON

You don't have to be Einstein to calculate the radius of a black hole's event horizon. In 1783 British natural philosopher John Michell predicted the existence of "dark stars" using Newtonian mechanics. He described an object that was compact enough that light particles leaving its surface would be slowed and then pulled back down by the star's gravity. Although photons don't actually slow down as Michell and others hypothesized, the formula for calculating a star's critical radius remains the same. For a nonspinning black hole, the event horizon's radius is $R=2GM/c^2$ where G is Newton's gravitational constant and c is the speed of light.

SHEPERD DOELEMAN

TEAMWORK Members of the Event Horizon Telescope project (plus one eavesdropper: the author is in the back row) gathered at the MIT Haystack Observatory in January 2010 to hash out their strategy. Sheperd Doeleman stands third from left in the back row.

water vapor can interfere with observations at this wavelength, making "high and dry" site conditions crucial. Astronomers have had some success with monitoring water-vapor fluctuations during observations and subtracting the effects from data later. EHT scientists also plan to use the Atacama Large Millimeter/submillimeter Array (ALMA), a network of 66 radio telescopes being assembled in northern Chile. Although ALMA has only about a third of its dishes in place it has already released its first images and begun an observing program. Astronomers will soon use the array to look at how Sgr A*'s behavior changes at different wavelengths, and the EHT team has already received international funding to phase ALMA with the global network.

ALMA is a "change in the firmament of VLBI," says Doeleman. Quite possibly the largest astronomy project in history, when completed it will have a resolution of less than 20 milliarcseconds at 345 GHz. If the EHT team can combine ALMA with seven to ten other antennas, astronomers should achieve an angular resolution of 20 *micro*arcseconds or better, clearly revealing Sgr A*'s silhouette.

EHT astronomers are hoping for a final list of stations committed to the project by 2015. During that time more facilities will come online, including the Large Millimeter Telescope (LMT), a joint American-Mexican project east of Mexico City that achieved first light last summer and has already signed onto the endeavor.

Meanwhile, observations are coming closer to revealing the secrets of black holes. Many astronomers are confident in the EHT, and the project received a thumb's up from the Astro2010 Decadal Survey. "We have the necessary technology and it was demonstrated to work on a smaller-scale project," says Loeb. "I think it's likely that the project will be successful."

Doeleman agrees. Advances in VLBI and our understanding of galactic centers make it almost certain that astronomers will directly image black hole silhouettes within the next decade, he says. And as new instruments come online, radio astronomers will want to observe at these wavelengths for a variety of projects, making observation time harder to come by in the future. *Now* is the time for the EHT, says Doeleman. "We should be bold." ✦

Camille M. Carlisle *is a former* S&T *intern who recently returned to the staff as assistant editor. This article is based on work from her MIT master's thesis, "Heart of Darkness."*